Particle Acceleration and Emission in Relativistic Jets

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Outline of talk

- Motivations
- Scientific goals
- Observations of accelerated particles
- MHD simulations of relativistic jets
- 1-D particle simulations of shock surfing model
- 3-D particle simulations of relativistic jets

  * Thin jets (electron-positron, electron-ion)

  * Flat jets (electron-positron, electron-ion)

  (infinitely wide) (parallel, perpendicular)
- Summary of present 3-D simulations (**Weibel Instability**)
- Future plans of relativistic particle simulations of relativistic jets

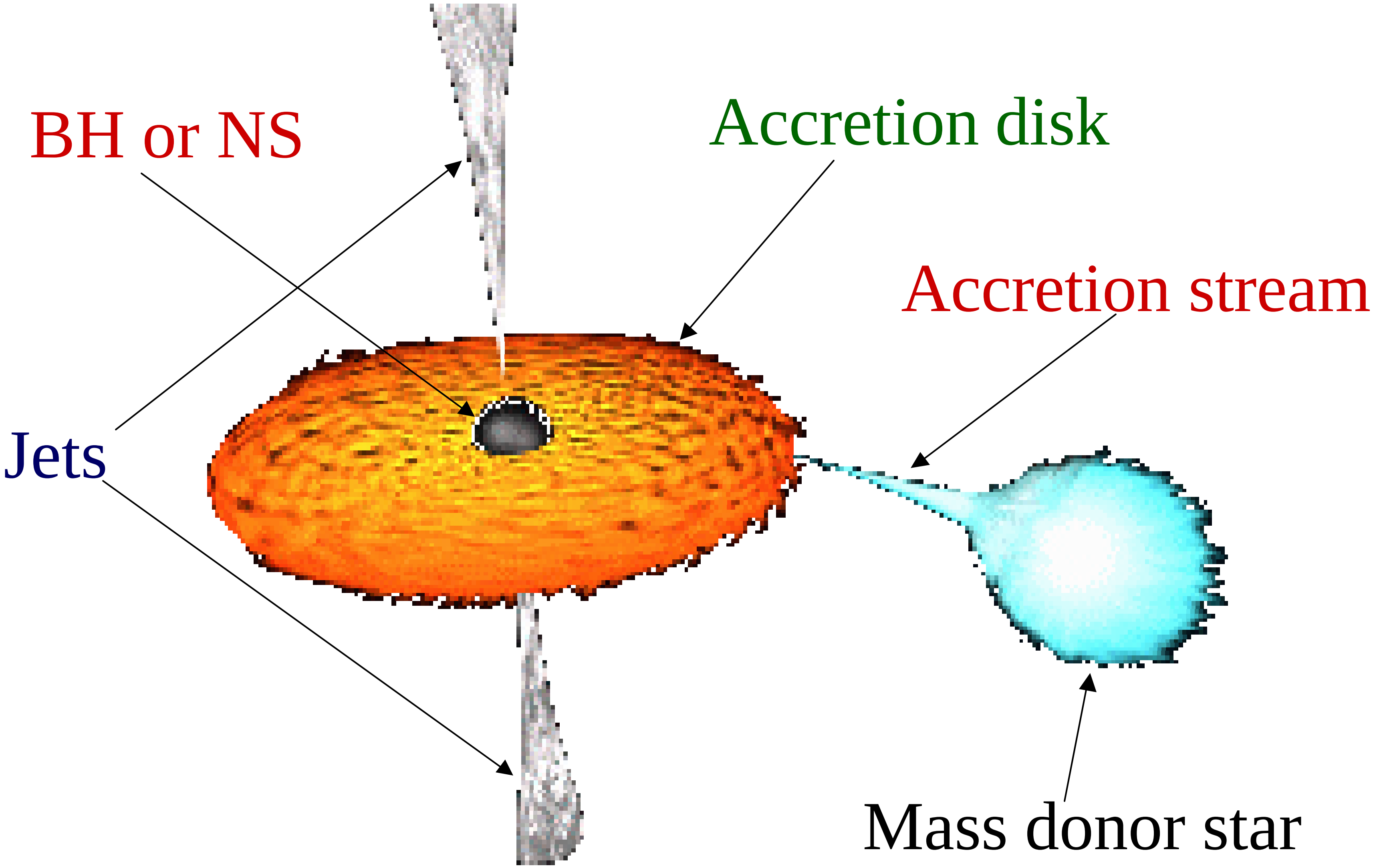
1. Motivations

- **Study particle acceleration at external and internal shocks in relativistic jets complimentary to RMHD and other test particle simulations using relativistic particle-in-cell simulations**
- **Examine the shock surfing acceleration in a 3-D system proposed in one-dimensional simulations including the dynamics of shock transition region**
- **Study structures and dynamics of shocks caused by instabilities at the shock front and transition region in relativistic jets**
- **Estimate synchrotron emission from accelerated particles**
- **Examine possibilities for afterglows in gamma-ray bursts with appropriate ambient plasmas**

Scientific objectives

- **How do shocks in relativistic jets evolve in accelerating particles and emission?**
- **Do reverse shocks create internal shocks ?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock front and transition region?**
- **What is the main acceleration mechanism in relativistic jets, shock surfing, wakefield, Fermi models or stochastic processes?**
- **How do shocks in relativistic jets evolve in the different ambient plasma and magnetic field conditions in various astrophysical phenomena?**

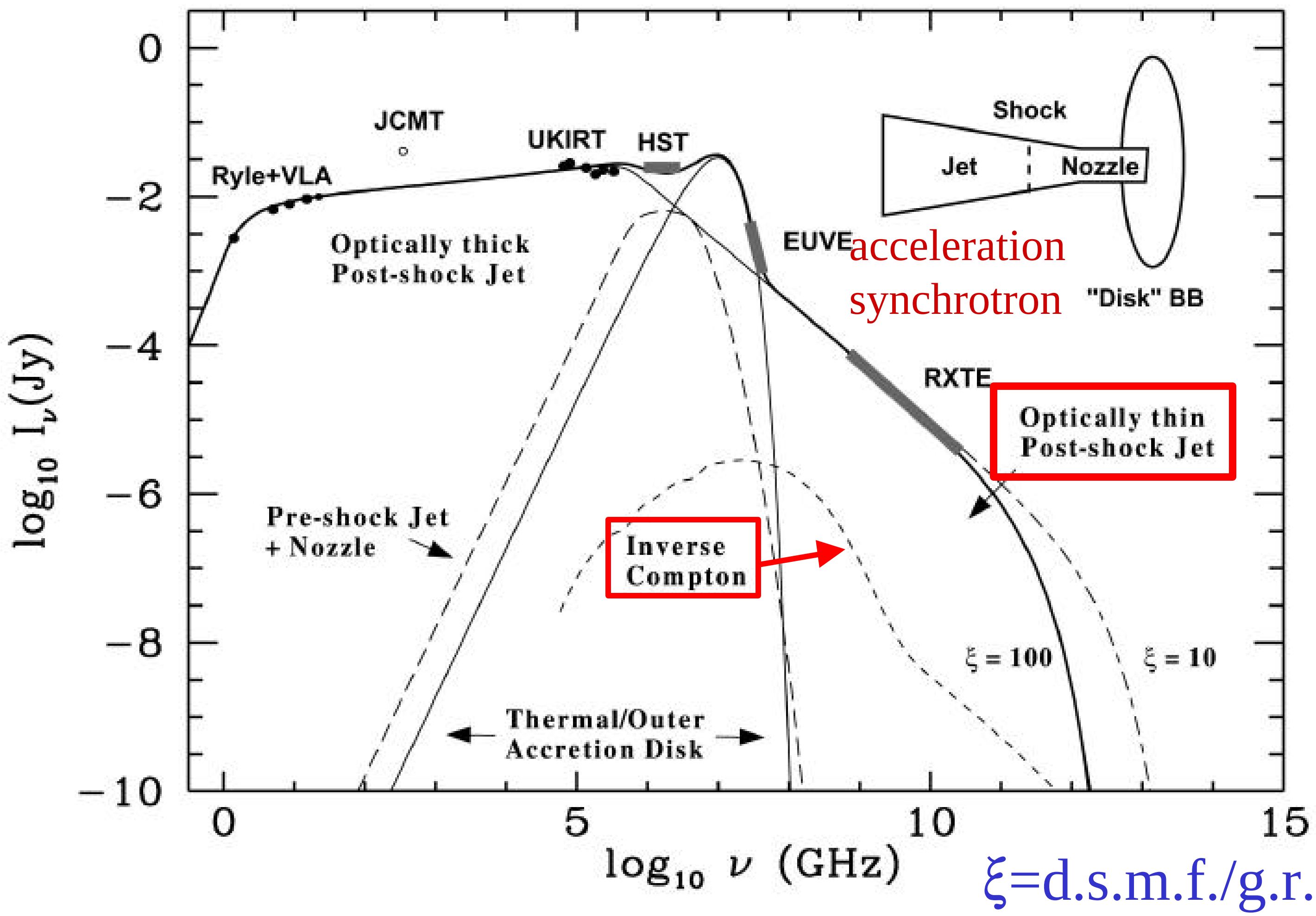
Jets from binary stars (Schematic figure)



Crab Nebula Pulsar Shrugs

a composite image of the center of Crab Nebula where red represents radio emission, green represents visible emission, and blue represents X-ray emission.

A jet model for the broadband spectrum of RXTE J1118+480



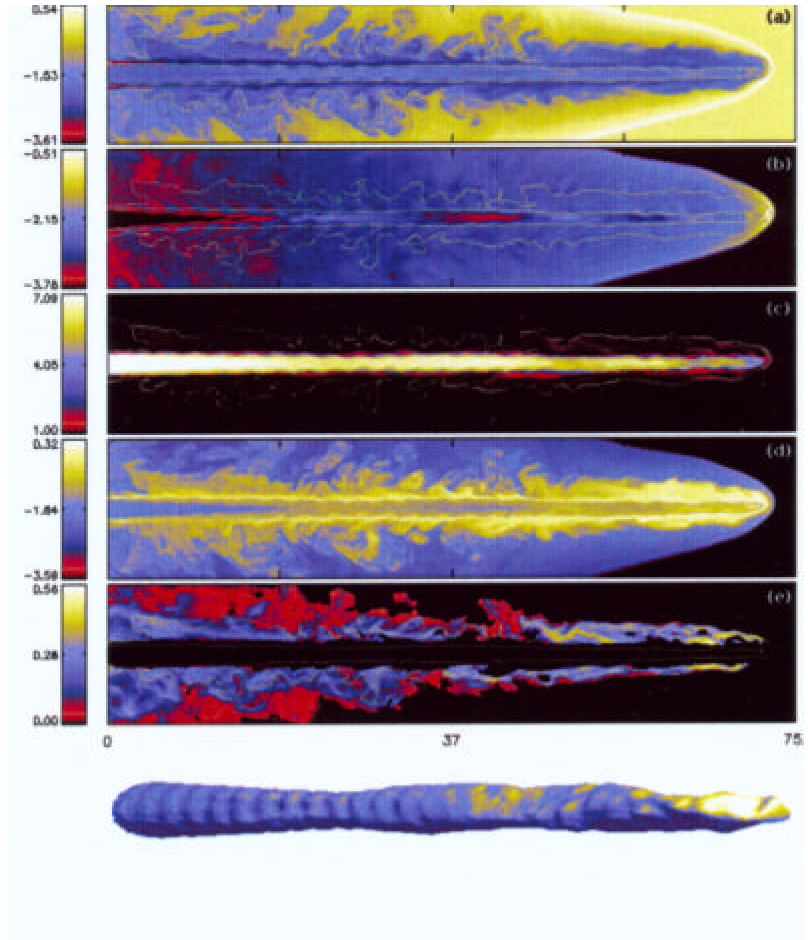
(Markoff, Falcke, & Fender, 2001, AA, 372, L25)

Relativistic jet (3-D RHD simulation)

(Aloy et al. 1999)

η=0.01, γ=5/3, v_b = 0.99c,
$W_b \approx$ 7.09, $v_h \approx 0.5c$,
with helical perturbation

t=152R_b/c



ρ

p

W_b

ϵ

v_{bf}

f=0.95

High resolution 3D simulations of relativistic jets

by

M.A. Aloy

in collaboration with

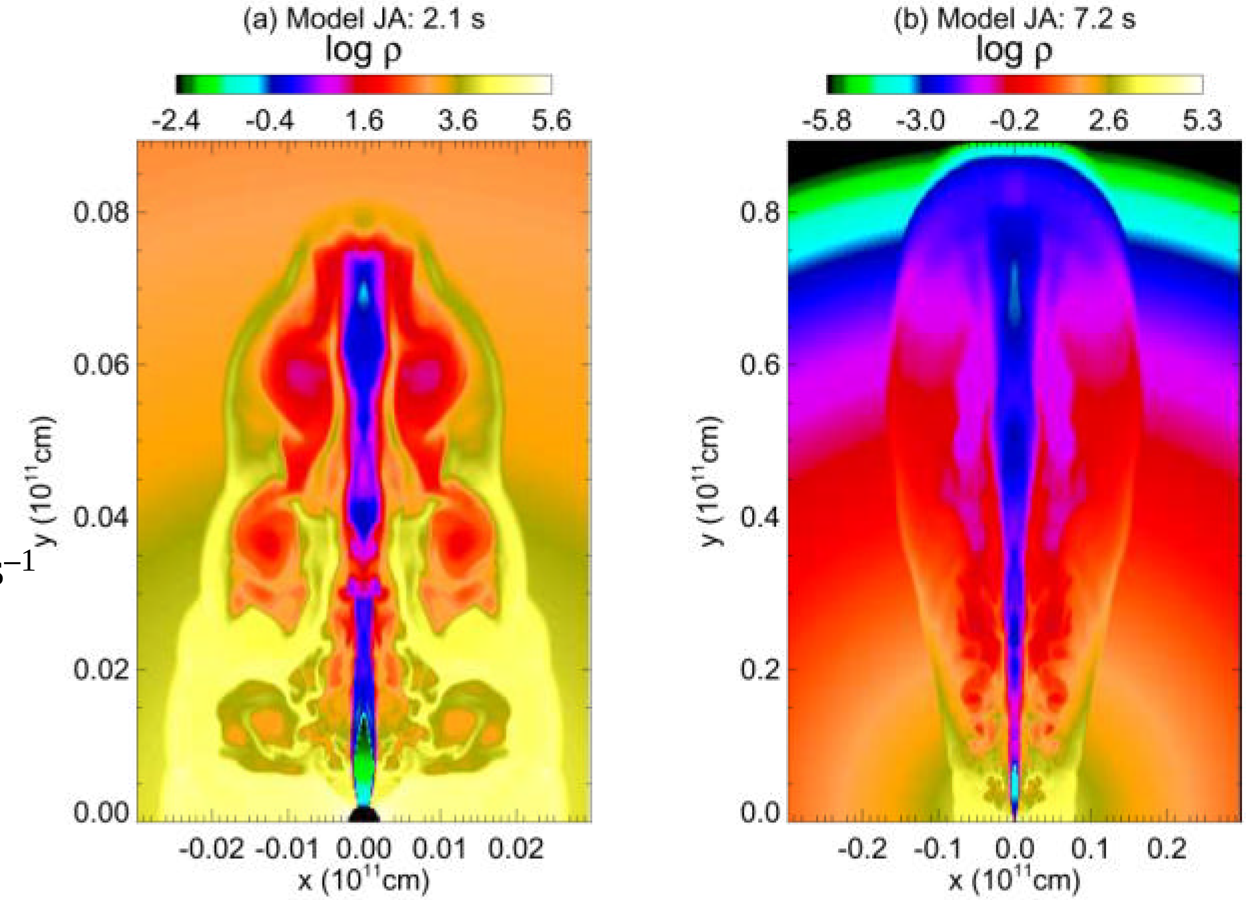
J.Mª Marti, J.Mª Ibañez & E. Mueller

Density structure of relativistic jet in collapsar

2-D RHD simulation

t = 2.1s

t = 7.2s



$\dot{E} = 1.0 \times 10^{51} \mathrm{erg\,s^{-1}}$

$\theta_0 = 20°$

$\Gamma_0 = 50$

$F_0 = 0.33$

(Zhang, Woosley, & MacFadyen, astro-ph/0207436)

3-D RMHD simulation (Γ = 4.56)

(Nishikawa et al. 1997)

Ideal fluid, Frozen condition

($t = 8.5\tau_S$)

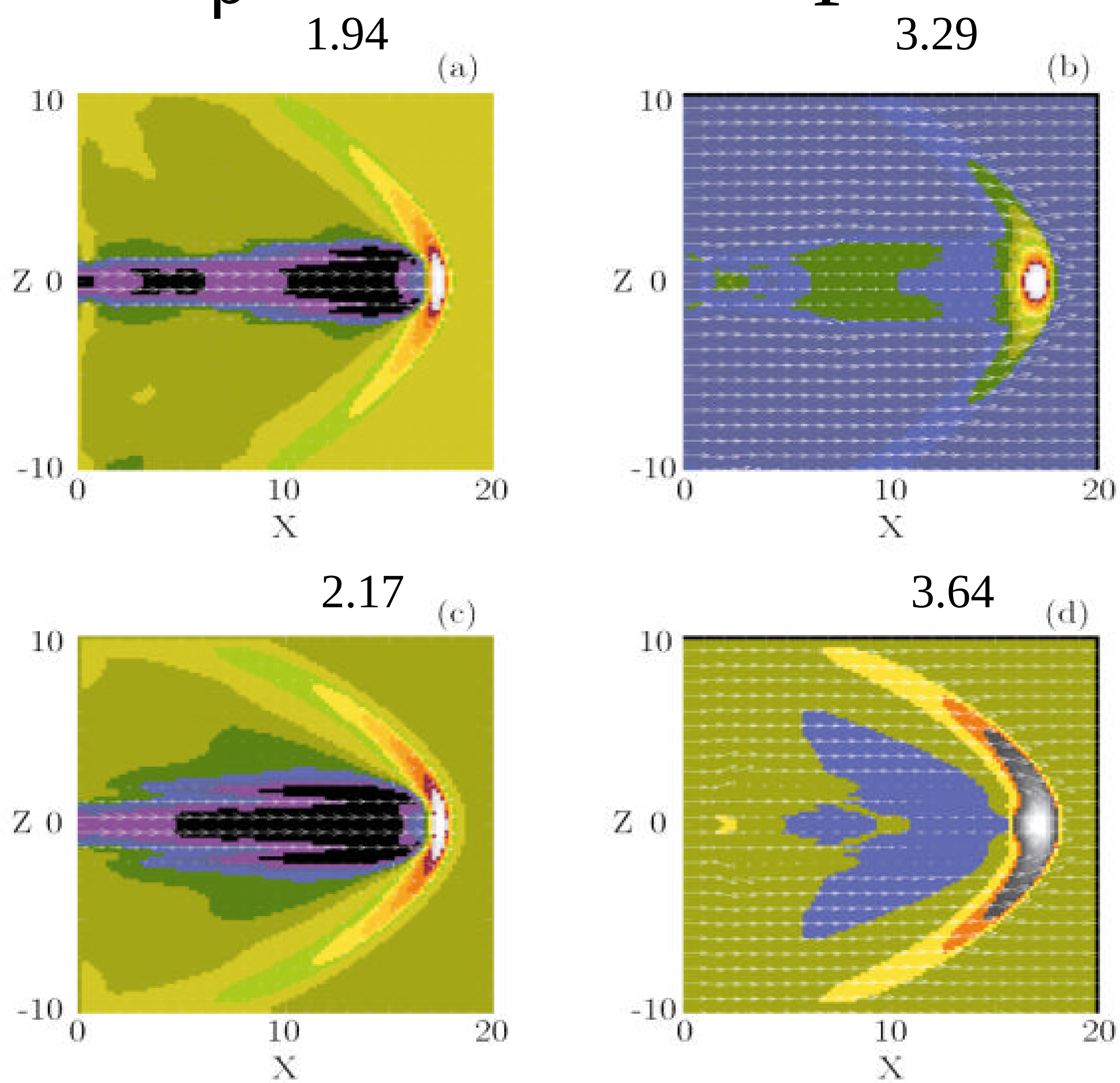
$\Gamma = 4.56$

$\eta = 0.3$

ρ P

Strong B-field

Weak B-field

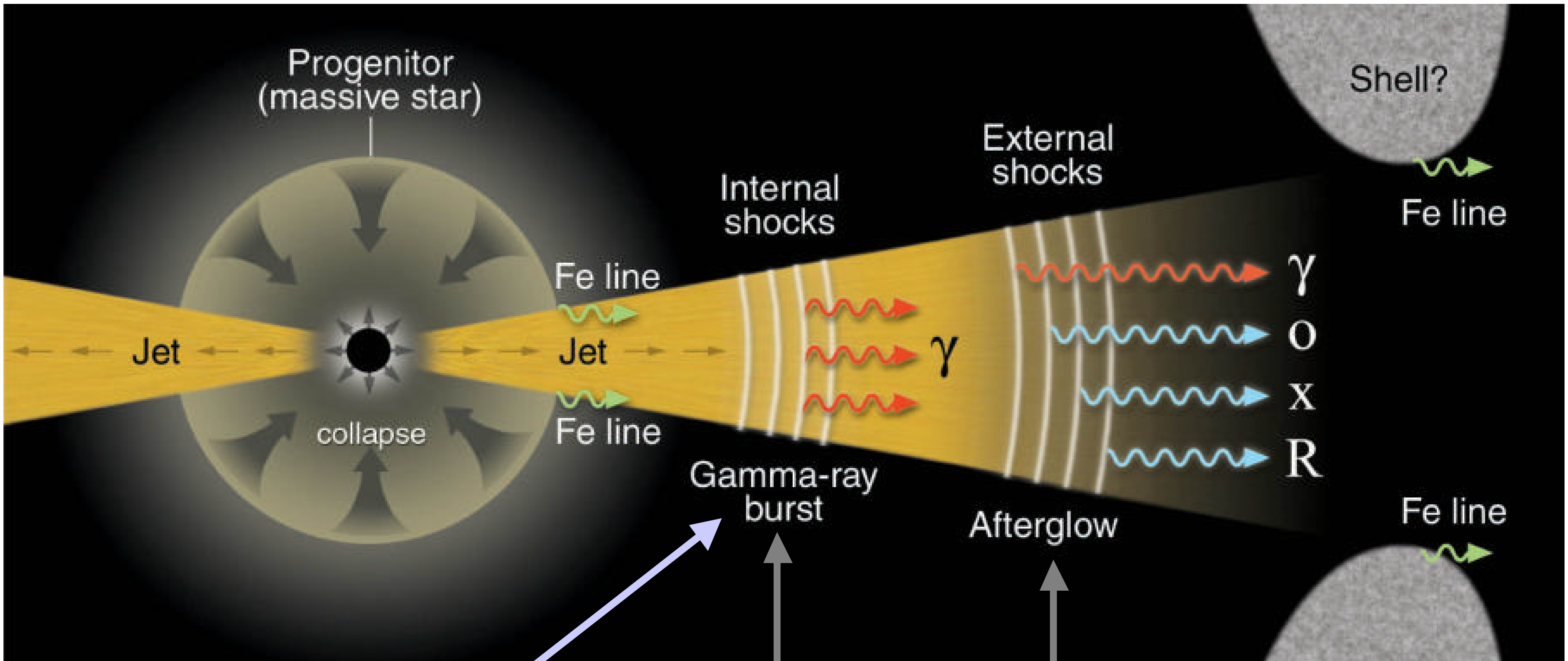


Necessity of particle simulation for particle acceleration

- **MHD simulations provide global dynamics of relativistic jets including hot spots**
- **MHD simulations include heating due to shocks, however do not create high energy particles (MHD simulation + test particle (Tom Jones))**
- **In order to take account of acceleration the kinetic effects need to be included**
- **Test particle (Monte Carlo) simulations can include kinetic effects, but not self-consistently**
- **Particle simulations provide particle acceleration and emission self-consistently, however due to the computational limitations, the size of jet is small comparing with MHD simulations**

Schematic GRB from a massive stellar progenitor

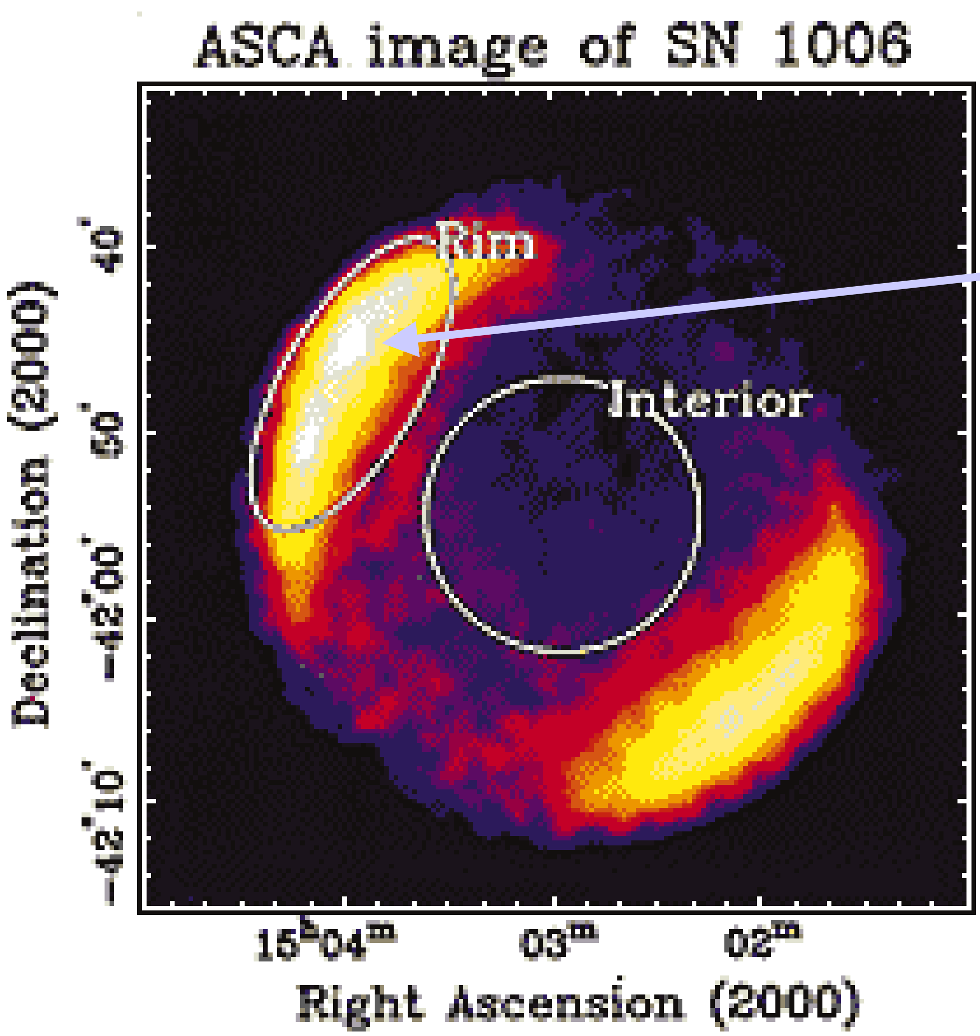
(Meszaros, Science 2001)



Prompt emission

Accelerated particles emit waves at shocks

Accelerated electrons (>TeV) in SN 1006

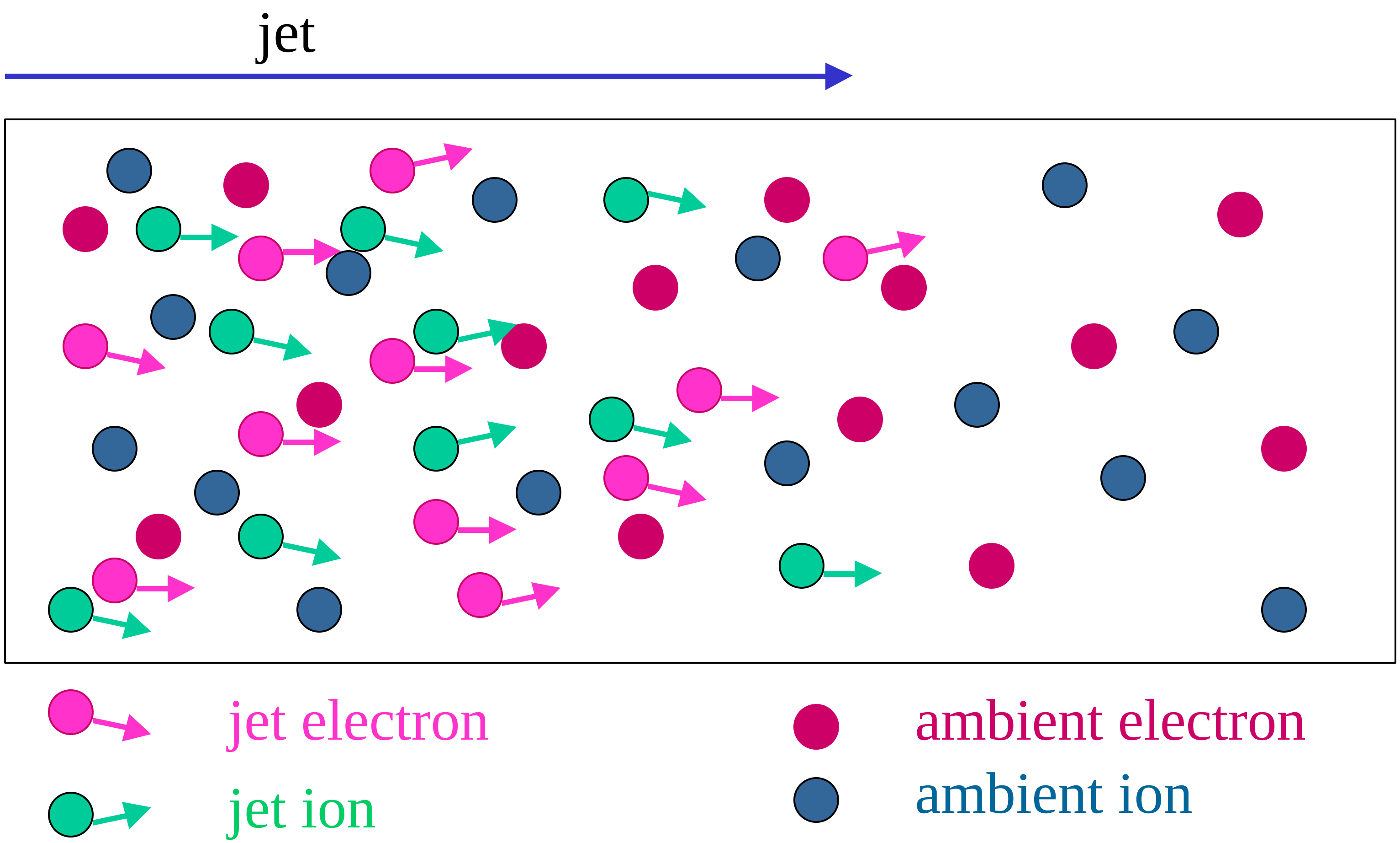


Shock is responsible for electron acceleration

Collisionless shock

Electric and magnetic fields created self-consistently by particle dynamics randomize particles

(Buneman 1993)



Magnetosonic shock structure in 1-D system

Buneman instability

reflected

ion

electron

U_{ix}/U_0

U_{ex}/U_0

$|U_e|/U_0$

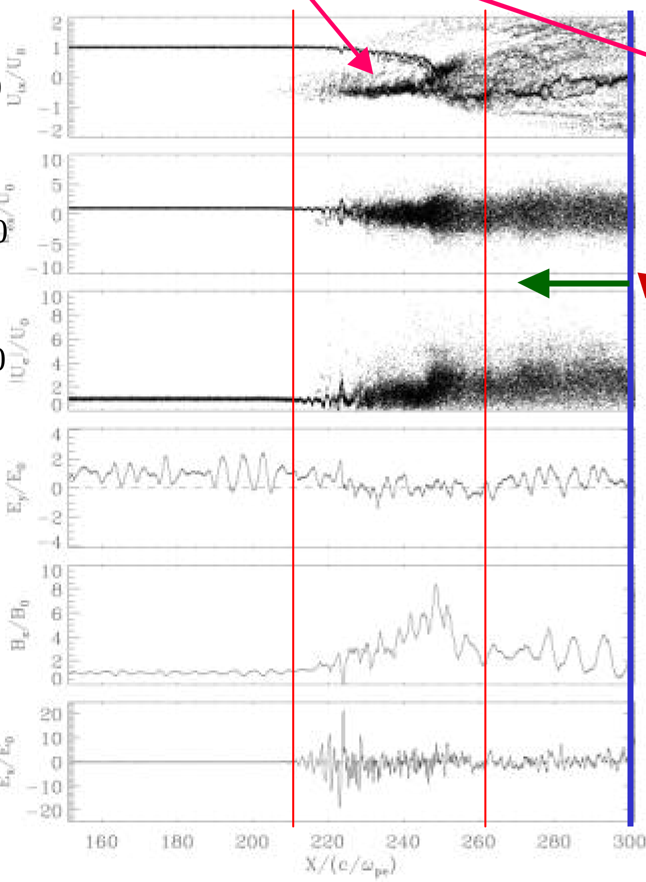
motional electric field

$E_y = v_0 B_0$

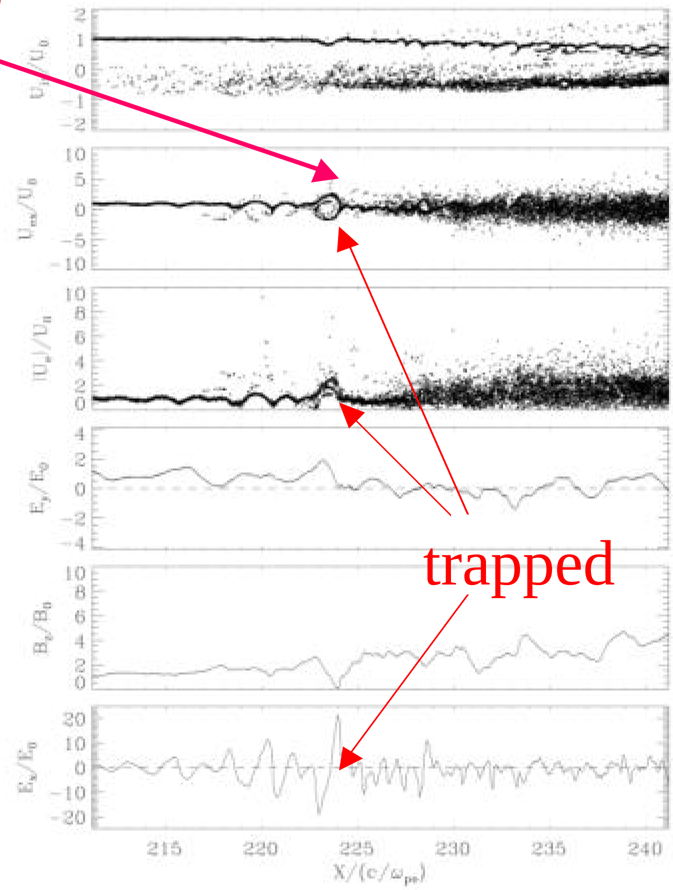
E_y/E_0

B_z/B_0

E_x/E_0



$X/(c/\omega_{pe})$



trapped

$X/(c/\omega_{pe})$

$\beta_e = \beta_i = 0.01$

$\omega_{pe}/\omega_{ce} = 19$

$m_i/m_e = 20$

$U_0 = 0.25c\ (0.375c)$

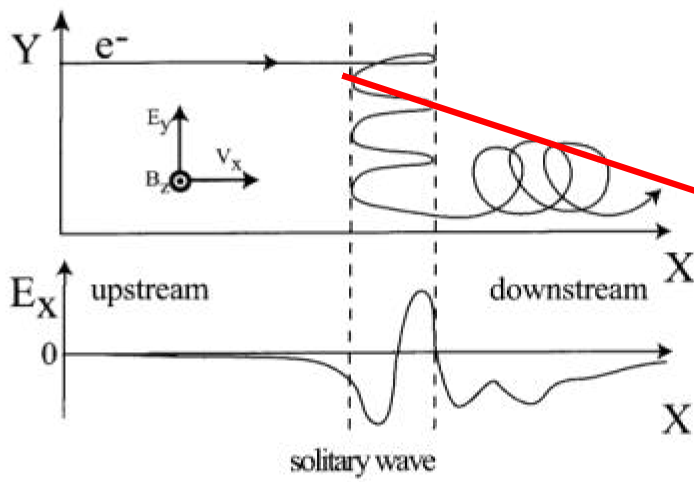
$V_A/c = 0.012$

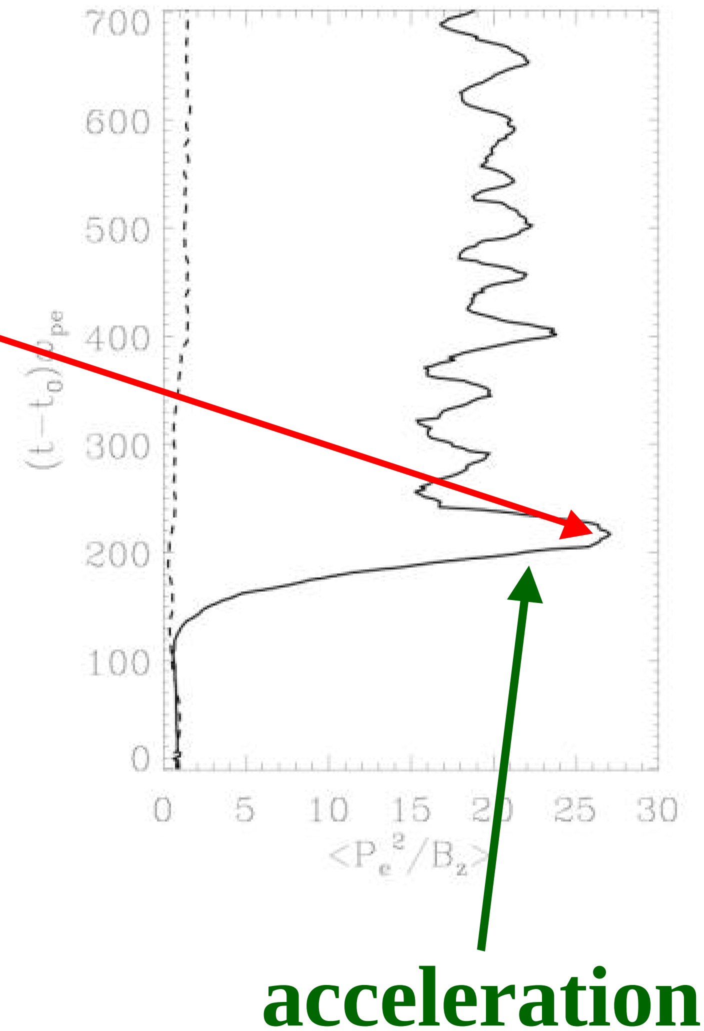
$M_A = 32$

$\gamma_0 \sim 1.03$

(Hoshino & Shimada, 2002, ApJ)

Illustration of the electron surfing mechanism

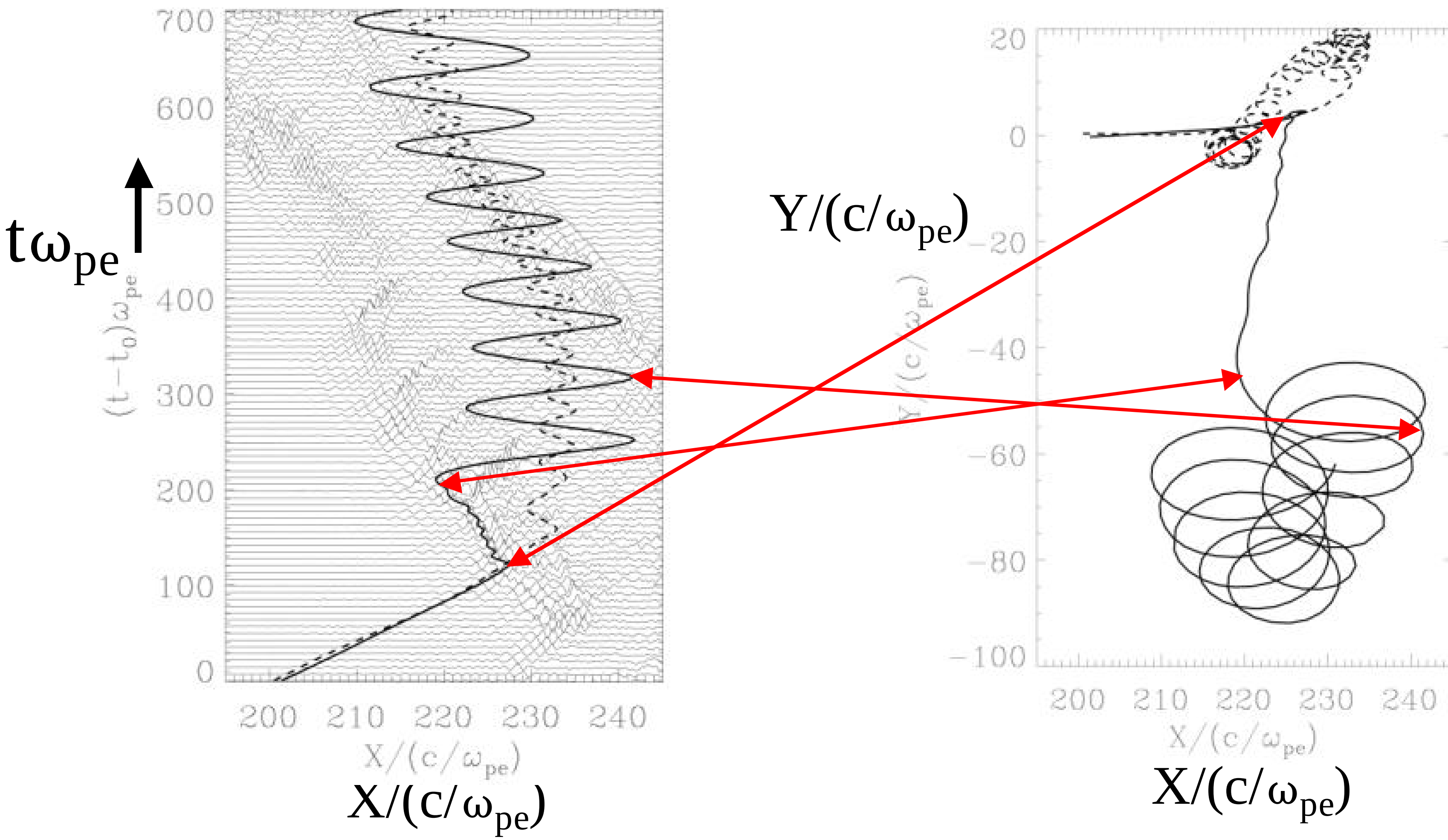




•How does this mechanism work in the 3-D shock transition regions?

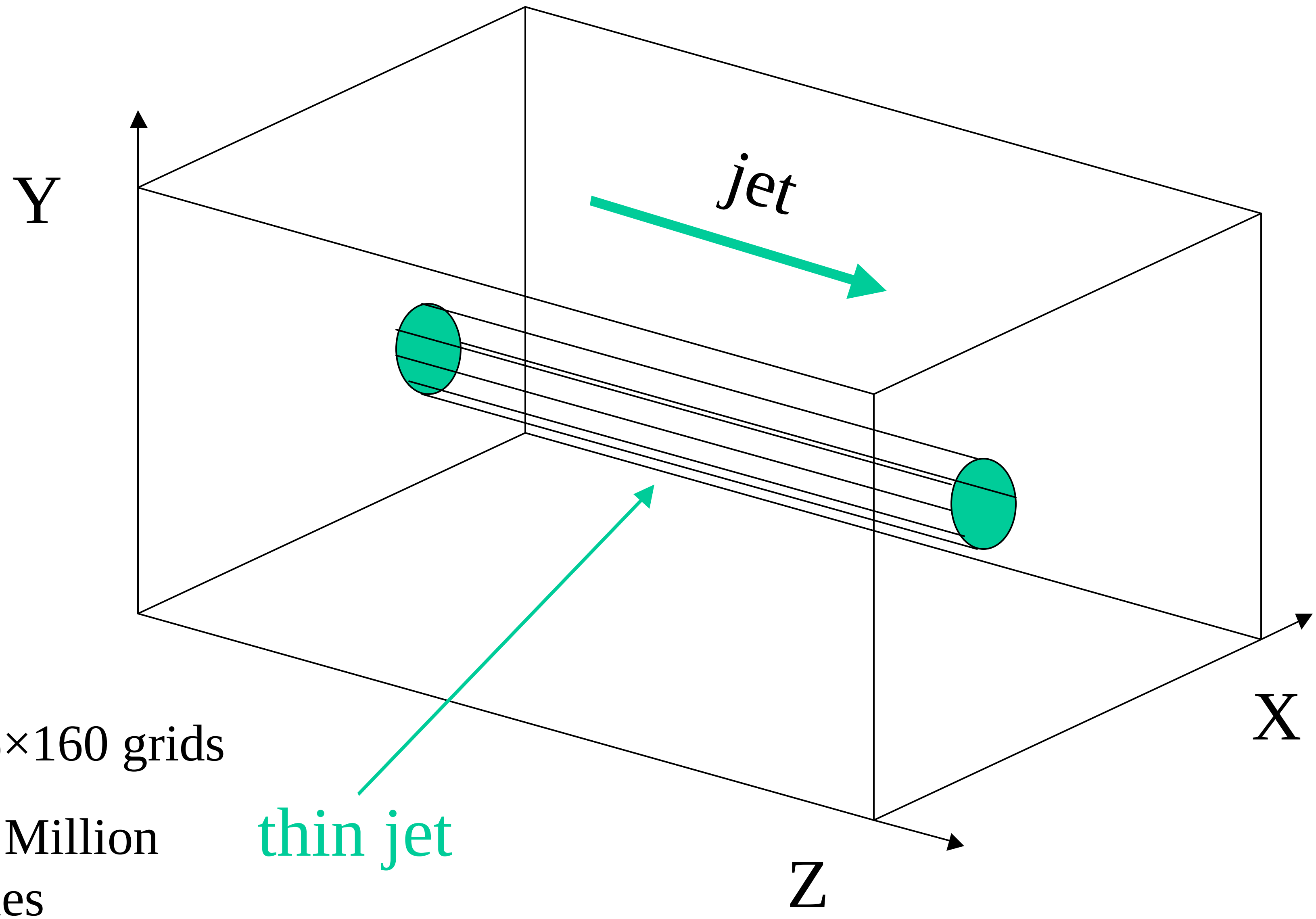
Time evolution of E_x and particle trajectories

Particle trajectories in x-y plane



3-D simulation

injected at z = 25Δ

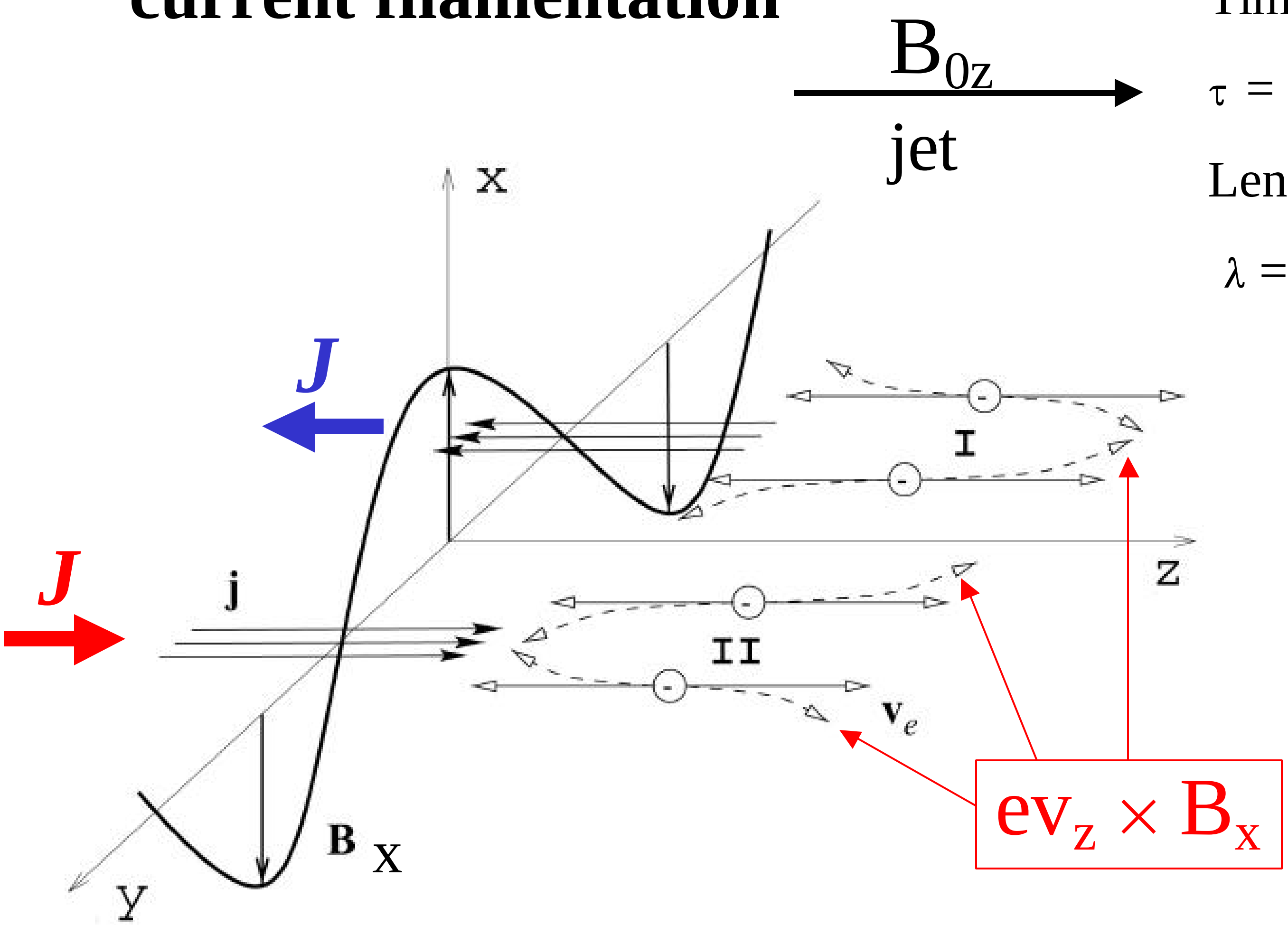


85×85×160 grids

55-85 Million particles

Weibel instability

current filamentation



Time:

$\tau = \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.5$

Length:

$\lambda = \gamma_{th}^{1/2} c/\omega_{pe} \approx 4.8\Delta$

(Medvedev & Loeb, 1999, ApJ)

3-D relativistic particle simulation of thin jet

Electron-positron jet, $m_i/m_e = 1$

$\beta = v_j/c = 0.9798$, $v_{et}/c = 0.1$

$\eta = n_j/n_a \approx 0.66$

$\gamma = (1-(v/c)^2)^{-1/2} = 5$ (Lorentz factor) ($\approx$ 5MeV)

$v_{je} = 0.1v_{et}$, $v_{ji} = 0.1v_{it}$

$\omega_{pe}/\Omega_e = 2.89$, $V_A/c = 0.346$,

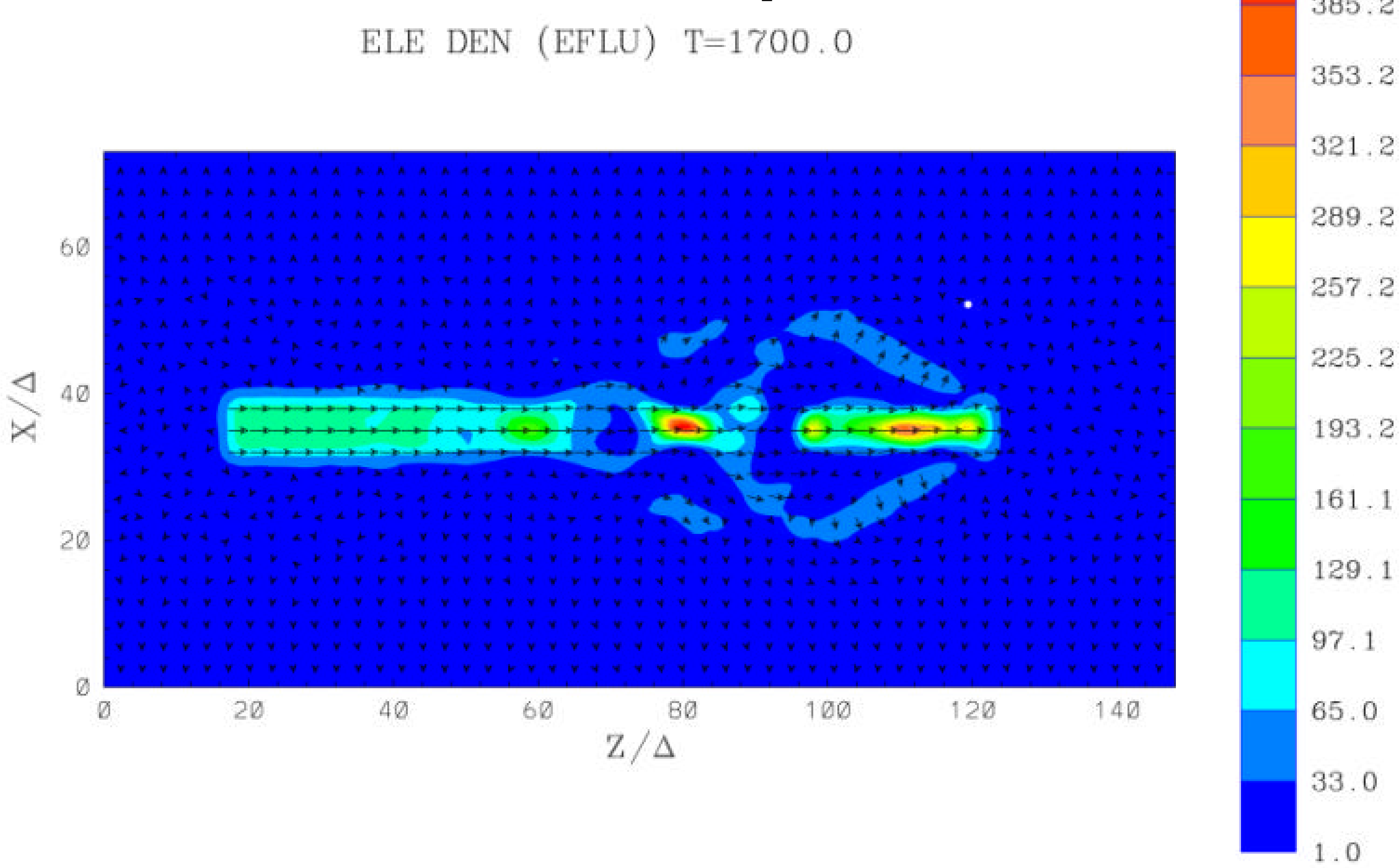
$\beta_e\ (=8\pi n_e T_e/B^2) = 1.66$, $M_A = v_j/V_A = 2.83$

$\omega_{pe}\Delta t = 0.013$, $r_j = 4\,\Delta x \approx \lambda_{ce}$ (jet radius)

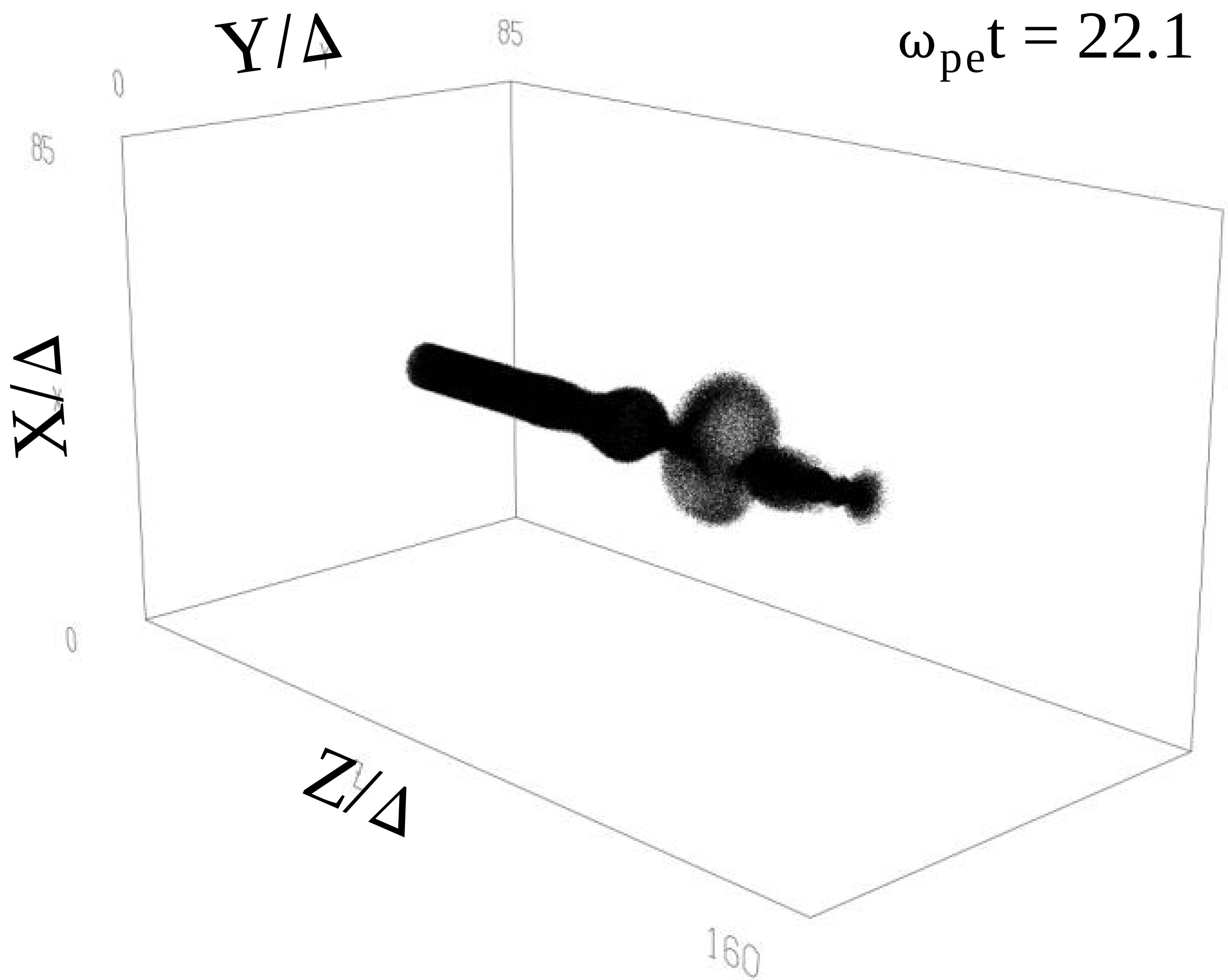
$\rho_e = 1.389\Delta$, $\rho_p = 1.389\Delta$

Thin electron-positron jet

$\omega_{pe}t = 22.1$



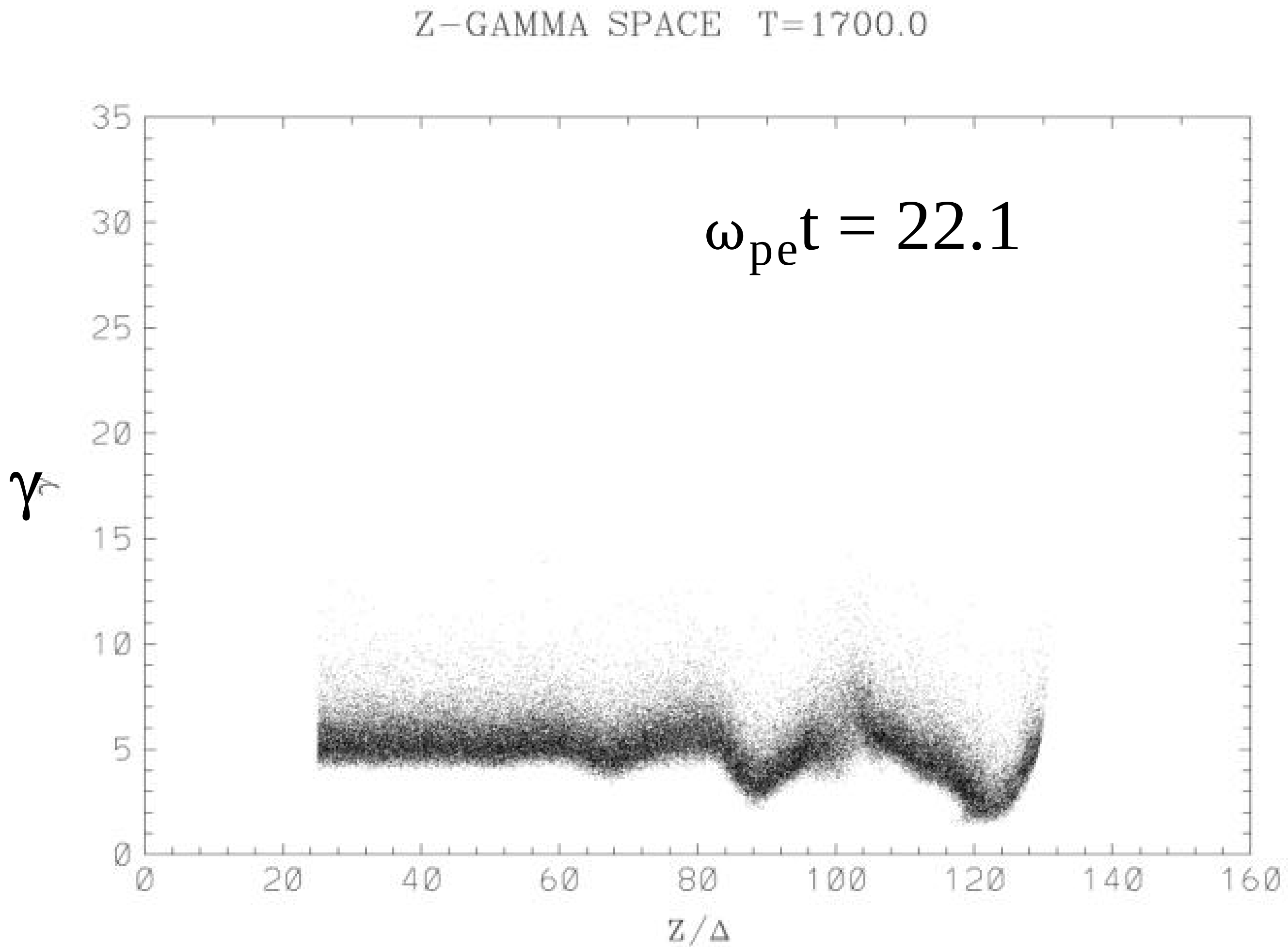
3-D structure of relativistic jet (electrons)



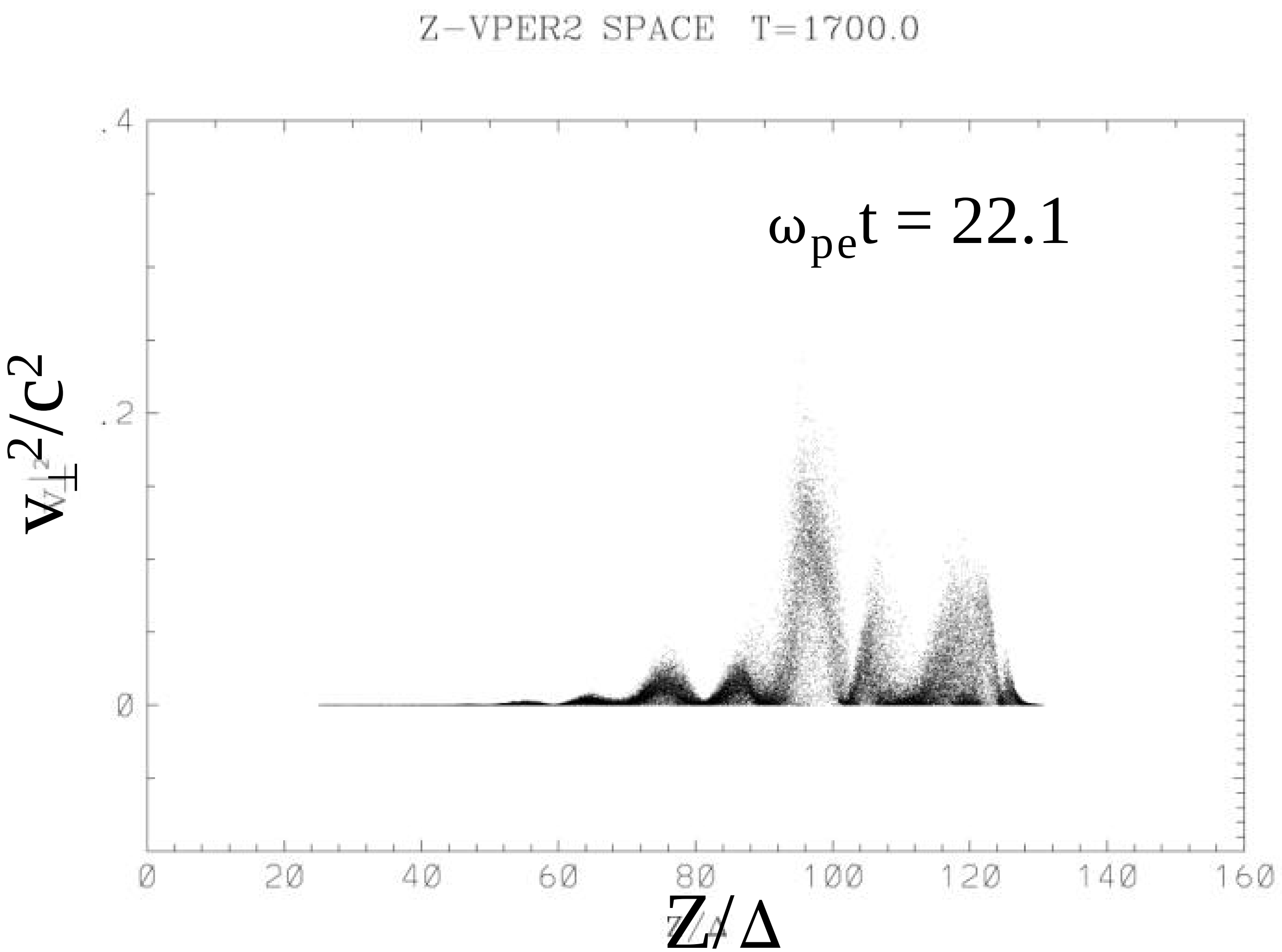
$\omega_{pe}t = 22.1$

Gamma of relativistic jet (electrons)

$\gamma = (1-(v/c)^2)^{-1/2}$



Perpendicular acceleration by shock



Electron-ion jet (thin)

Electron-ion jet, $m_i/m_e = 20$

$\beta = v_j/c = 0.9798$, $v_{et}/c = 0.1$

$\eta = n_j/n_a \approx 0.66$

$\gamma = (1-(v/c)^2)^{-1/2} = 5$

$v_{je} = 0.1v_{et}$, $v_{ji} = 0.1v_{it}$, $v_{it} = 0.224v_{et}$

$\omega_{pe}/\Omega_e = 2.89$, $V_A/c = 0.0775$, $M_A = 12.65$

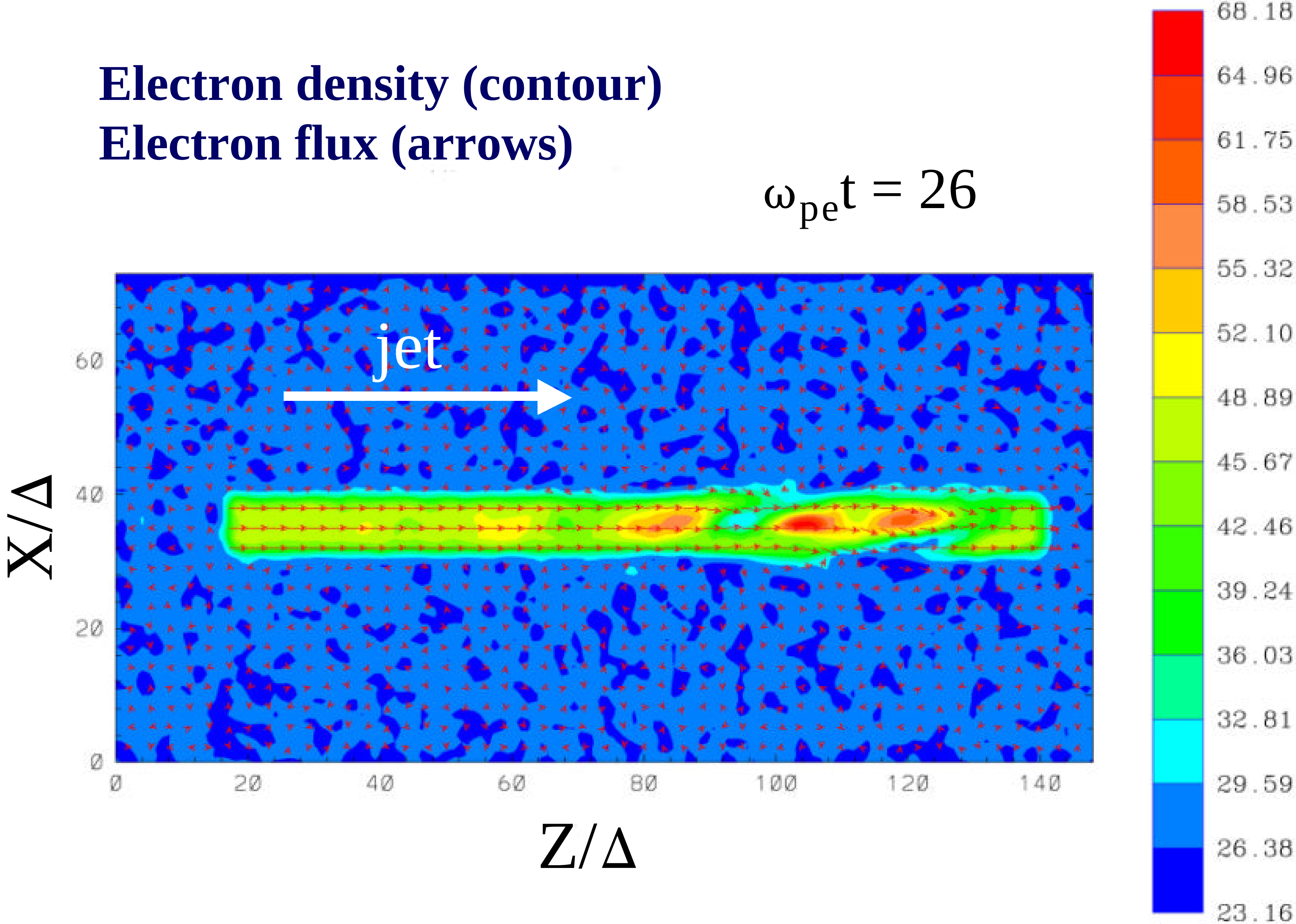
β_e $(=8\pi n_e T_e/B^2) = 0.167$

$\omega_{pe}\Delta t = 0.026$, $r_j = 4\,\Delta x \approx \lambda_{ce}$

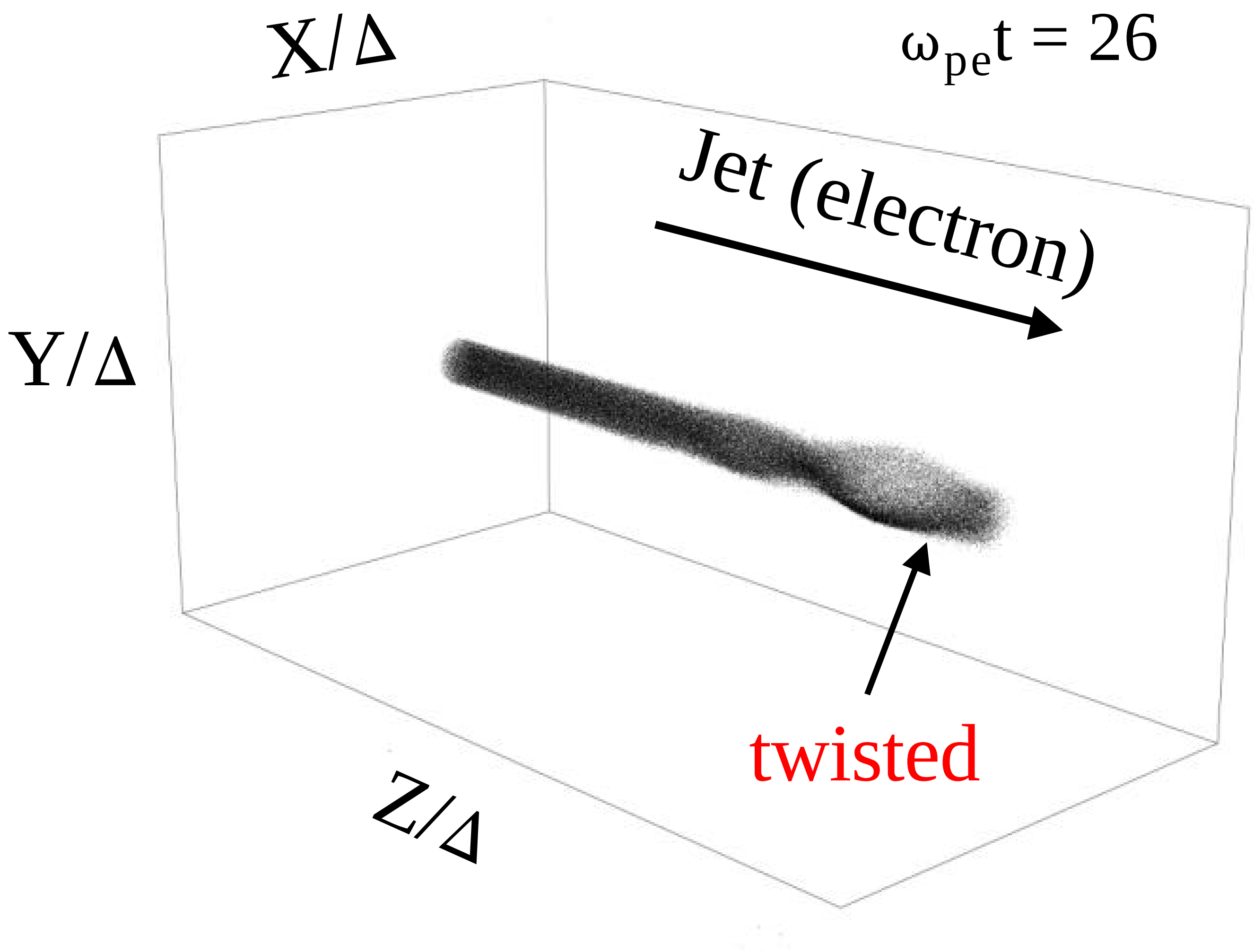
$\rho_e = 1.389\Delta$, $\rho_i = 6.211\Delta$

Thin electron-ion jet

Electron density (contour)
Electron flux (arrows)

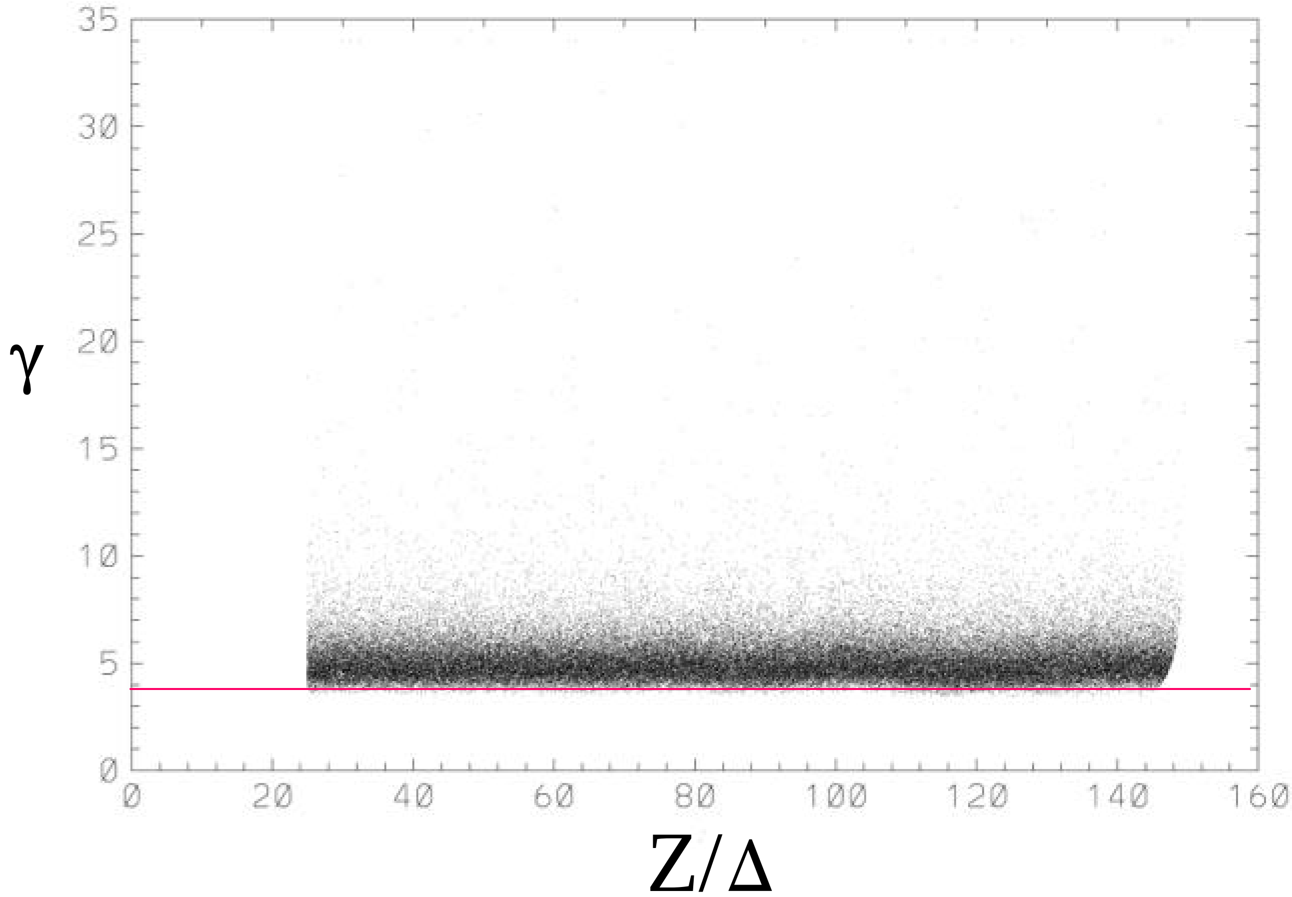


Electron-ion jet (thin)

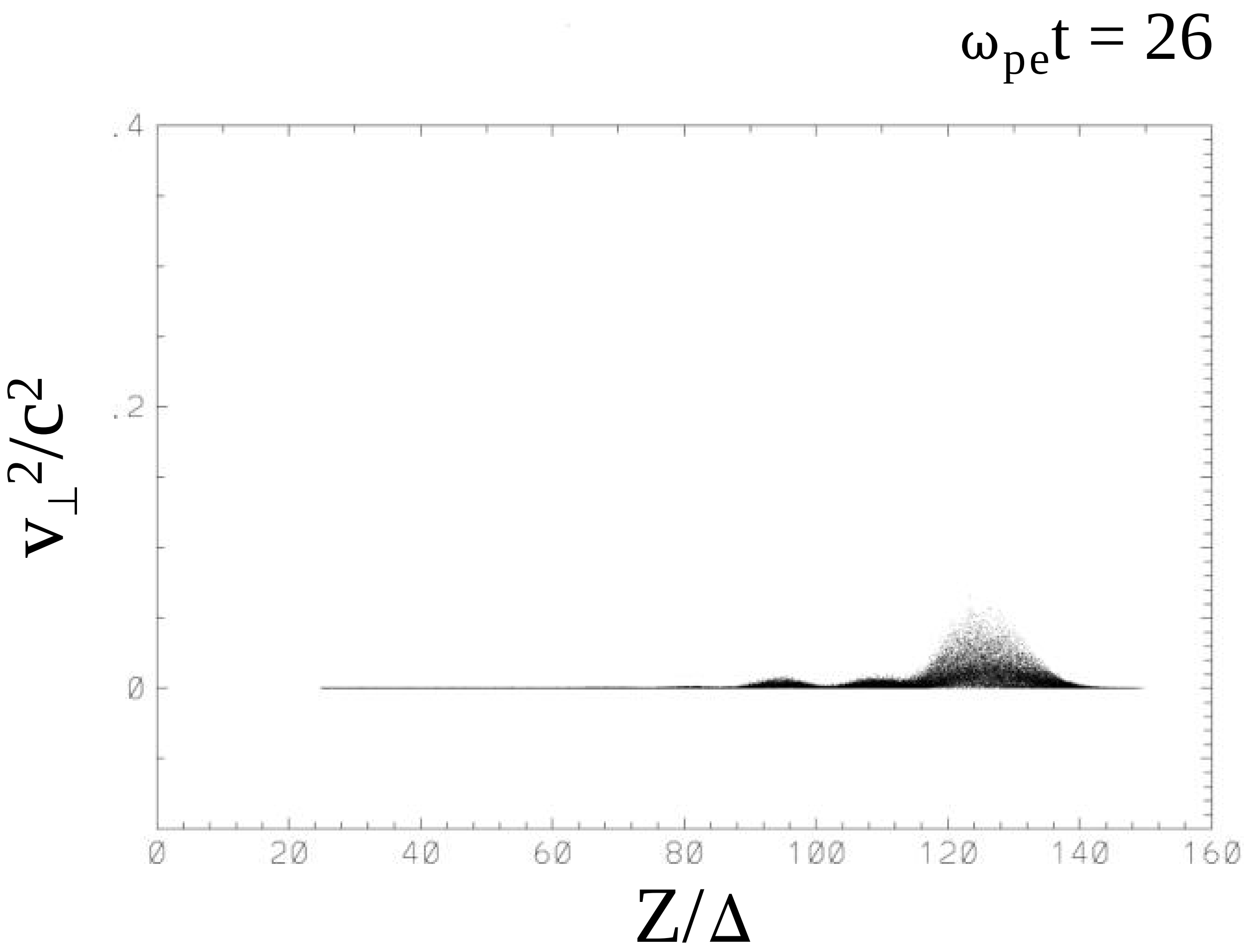


Lorenz factor of electron jet $\gamma = (1-(v/c)^2)^{-1/2}$

$\omega_{pe}t = 26$

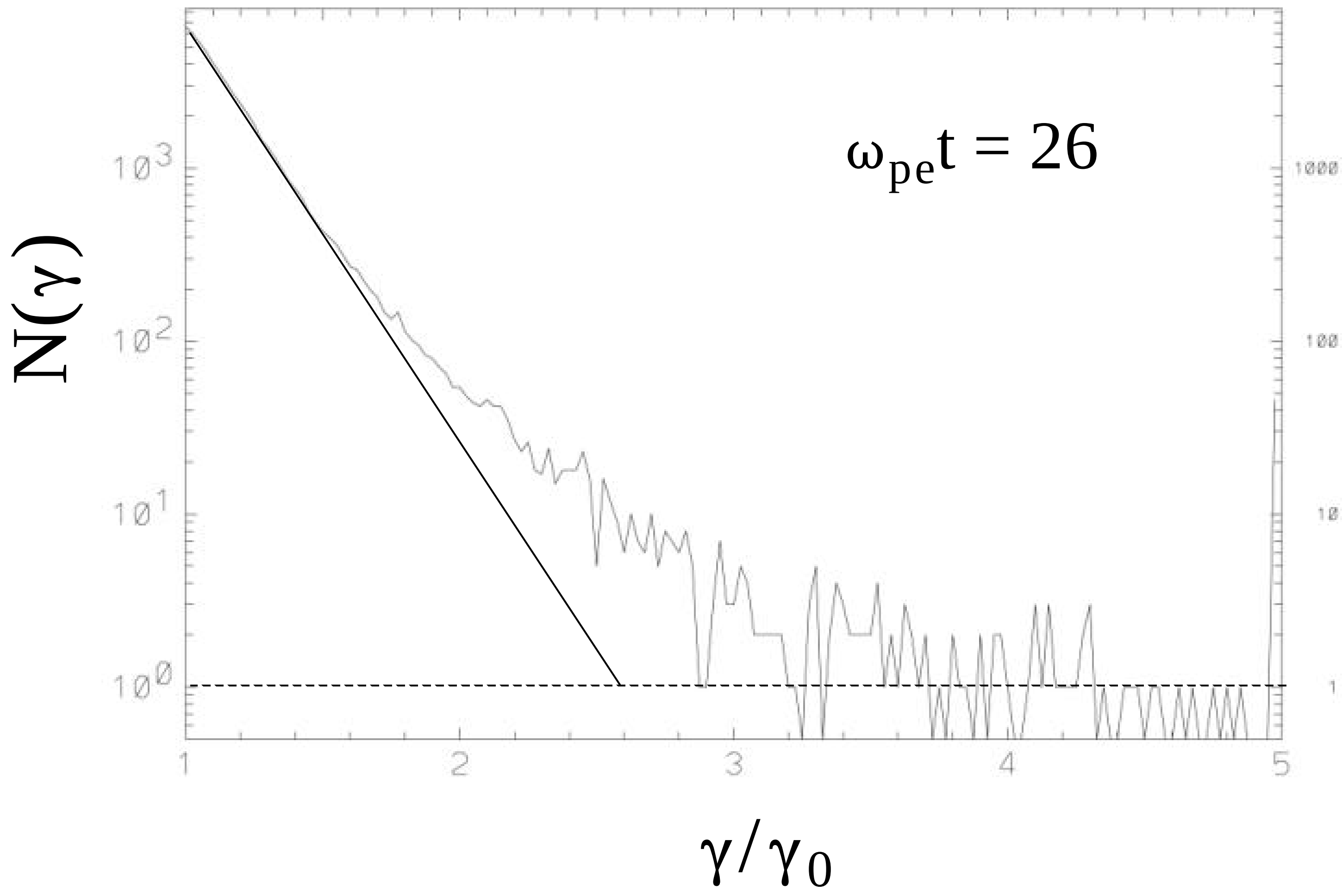


Acceleration in perpendicular velocity (electron)

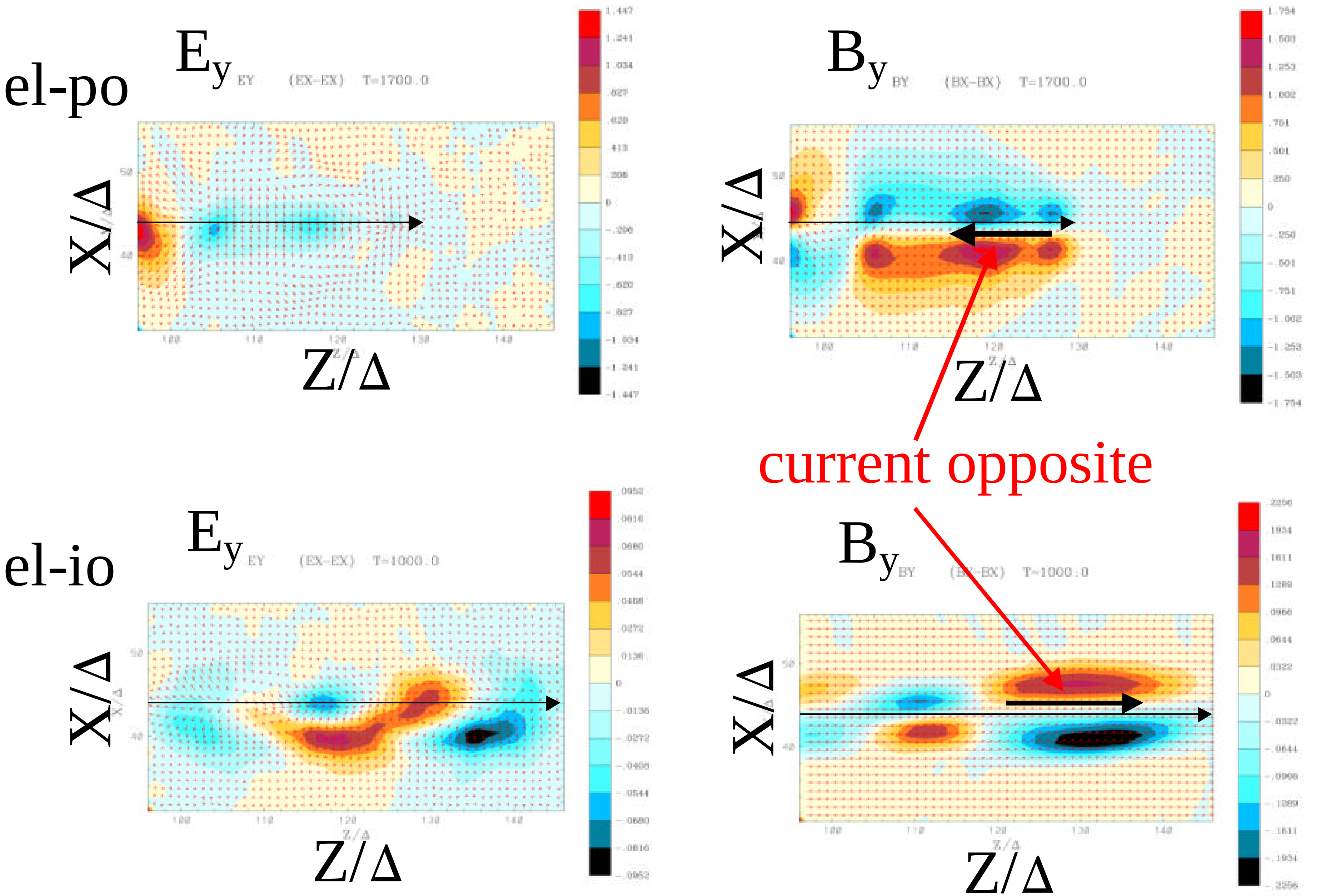


Suprathermal electron energy

electron-ion



Structure of jet head



Flat jet injected parallel to B

Electron-ion jet, $m_i/m_e = 20$

$\beta = v_j/c = 0.9798$, $v_{et}/c = 0.1$

$\eta = n_j/n_a \approx 0.85$

$\gamma = (1-(v/c)^2)^{-1/2} = 5$

$v_{je} = 0.1v_{et}$, $v_{ji} = 0.1v_{it}$, $v_{it} = 0.0111$

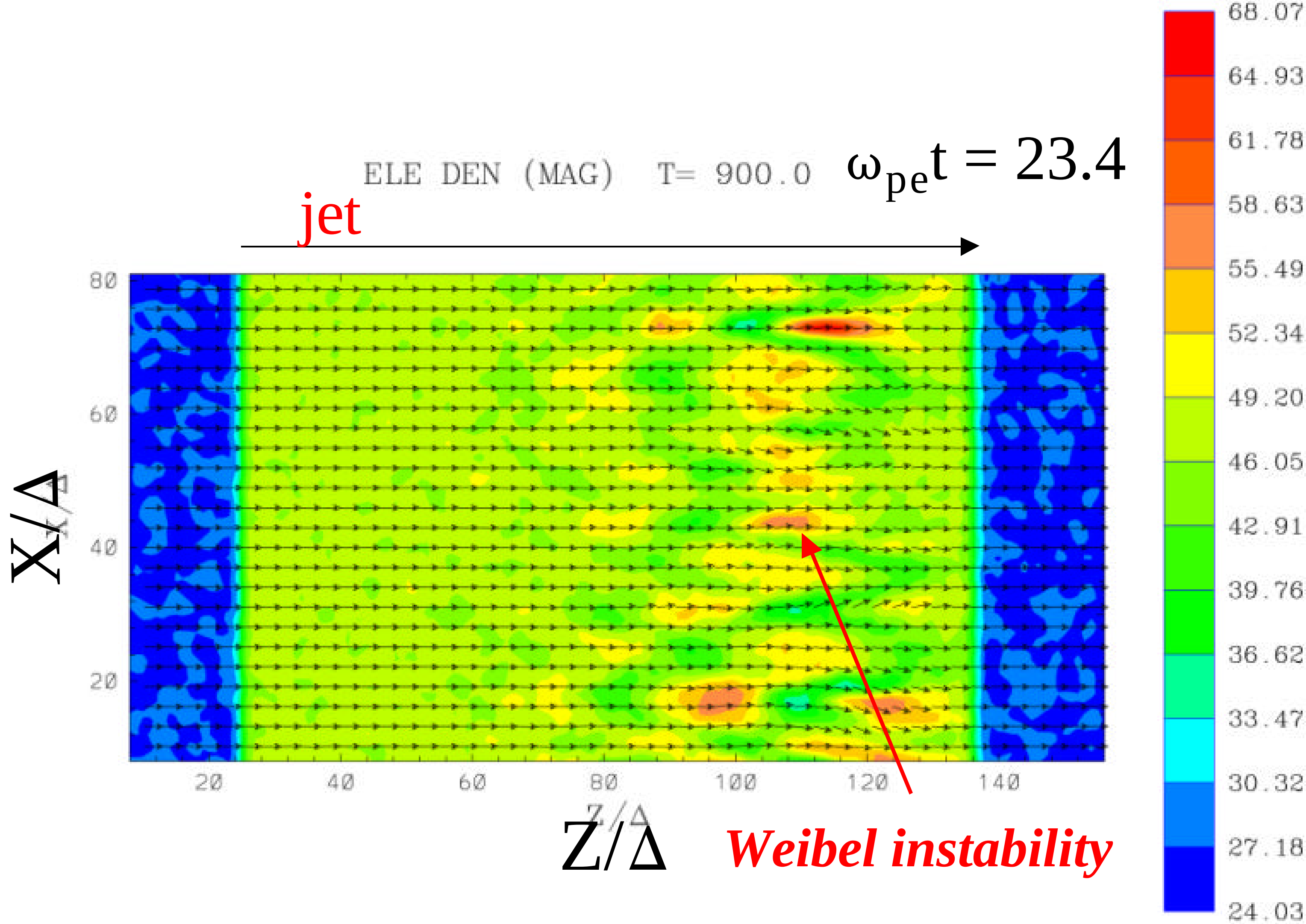
$\omega_{pe}/\Omega_e = 2.89$, $V_A/c = 0.0775$, $M_A = 12.65$

$\beta_e\ (=8\pi n_e T_e/B^2) = 1.66$

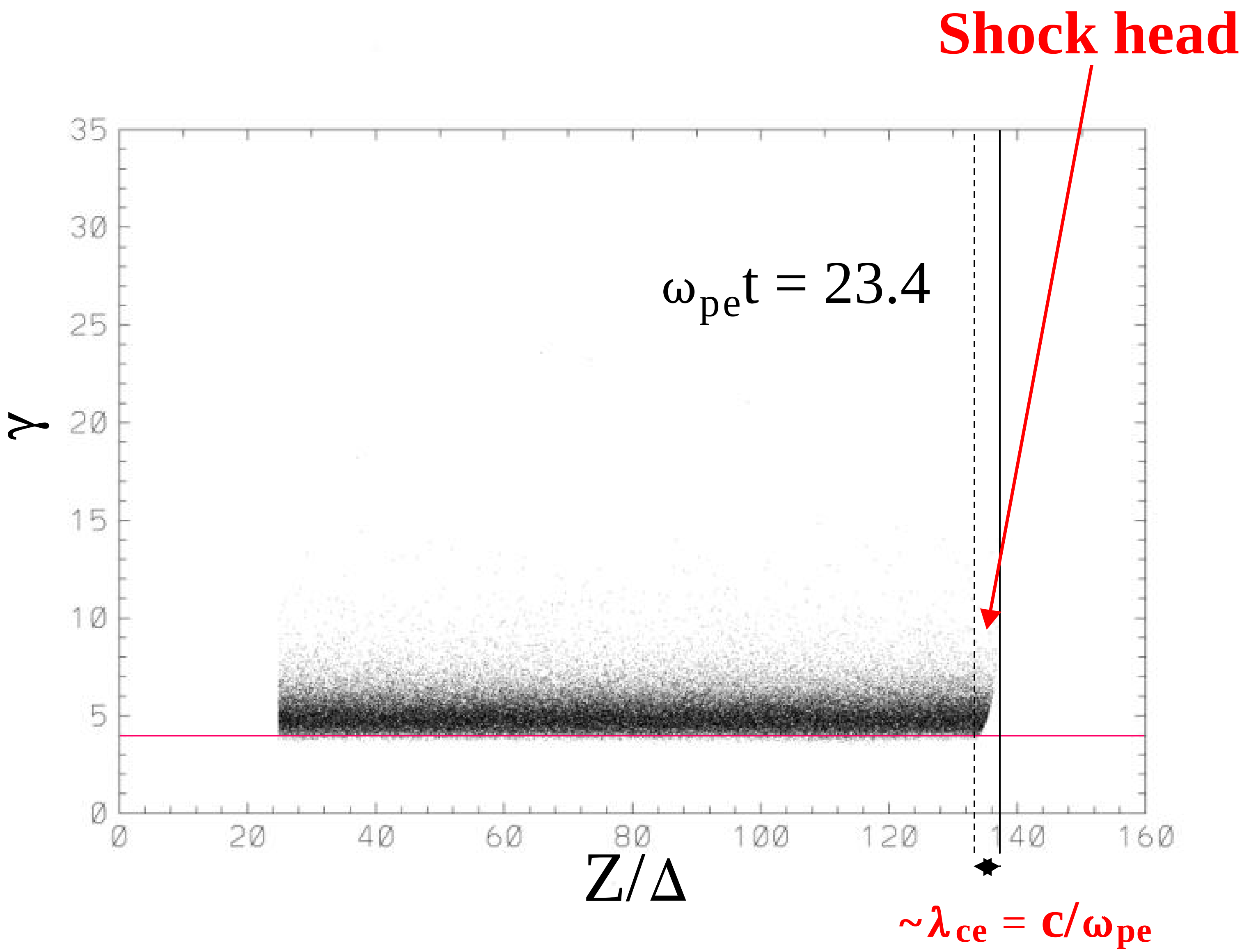
$\omega_{pe}\Delta t = 0.026$, $r_j = 40\ \Delta x \approx 10\ \lambda_{ce}$ (infinite)

$\rho_e = 1.389\Delta$, $\rho_i = 6.211\Delta$

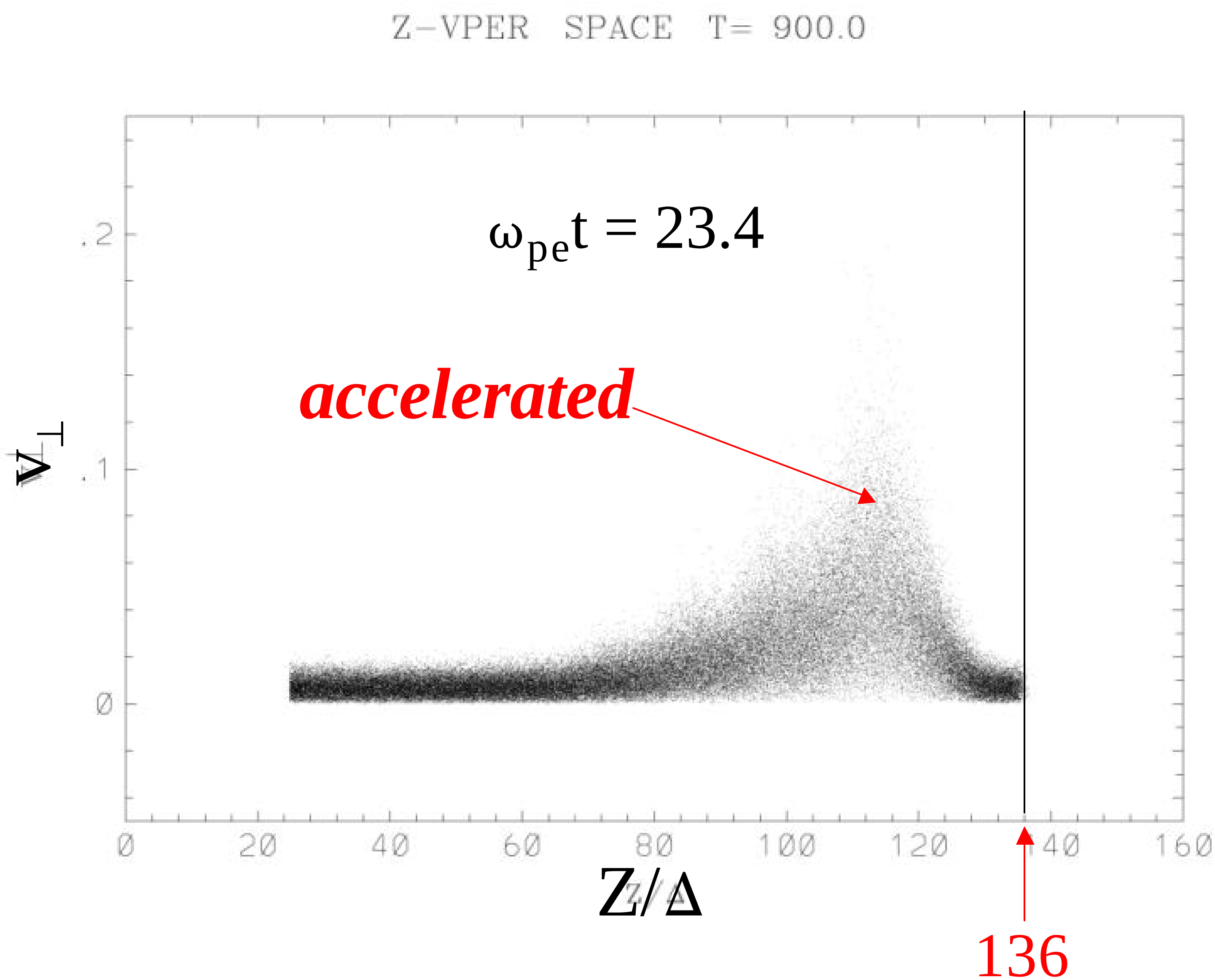
Electron density (arrows: B_z, B_x)



Lorenz factor of jet electron



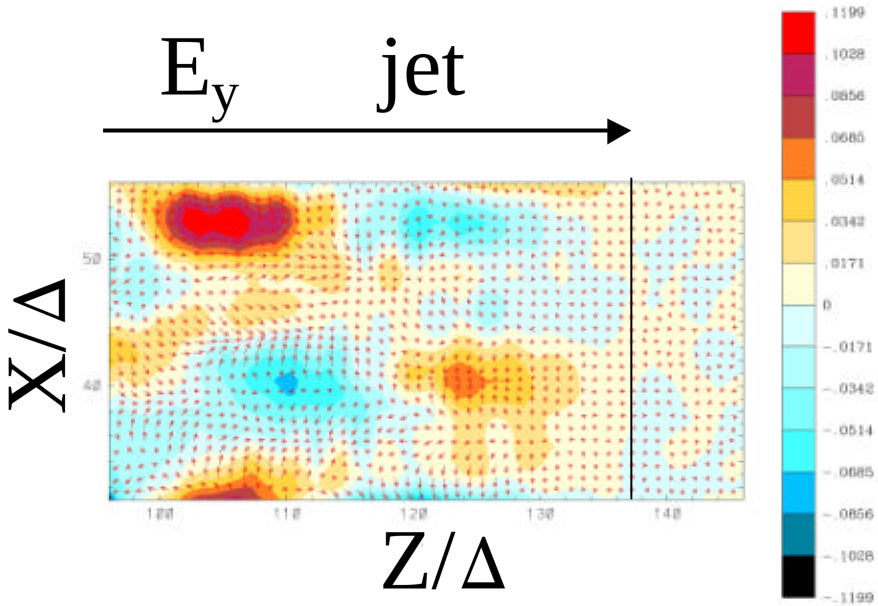
Perpendicular acceleration of jet electron

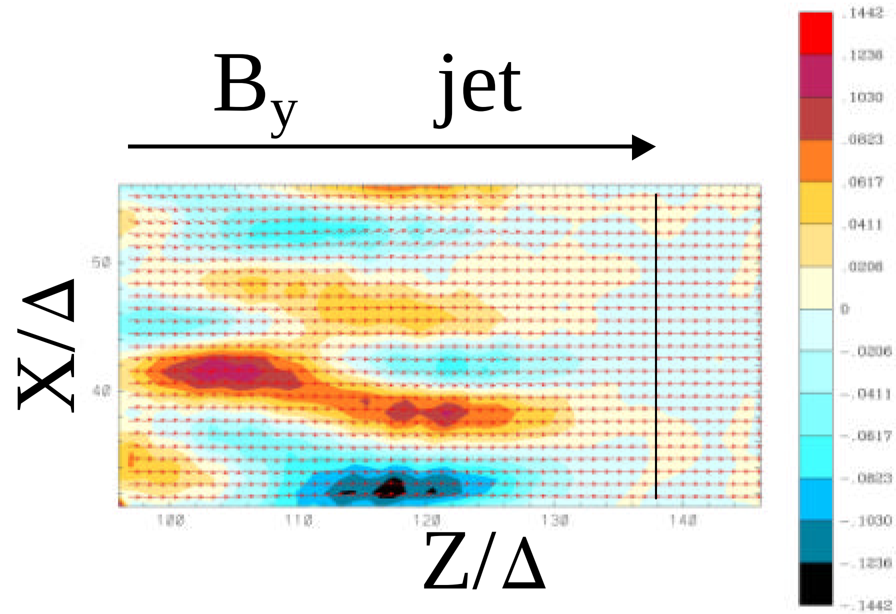


Weibel instability in the transition region

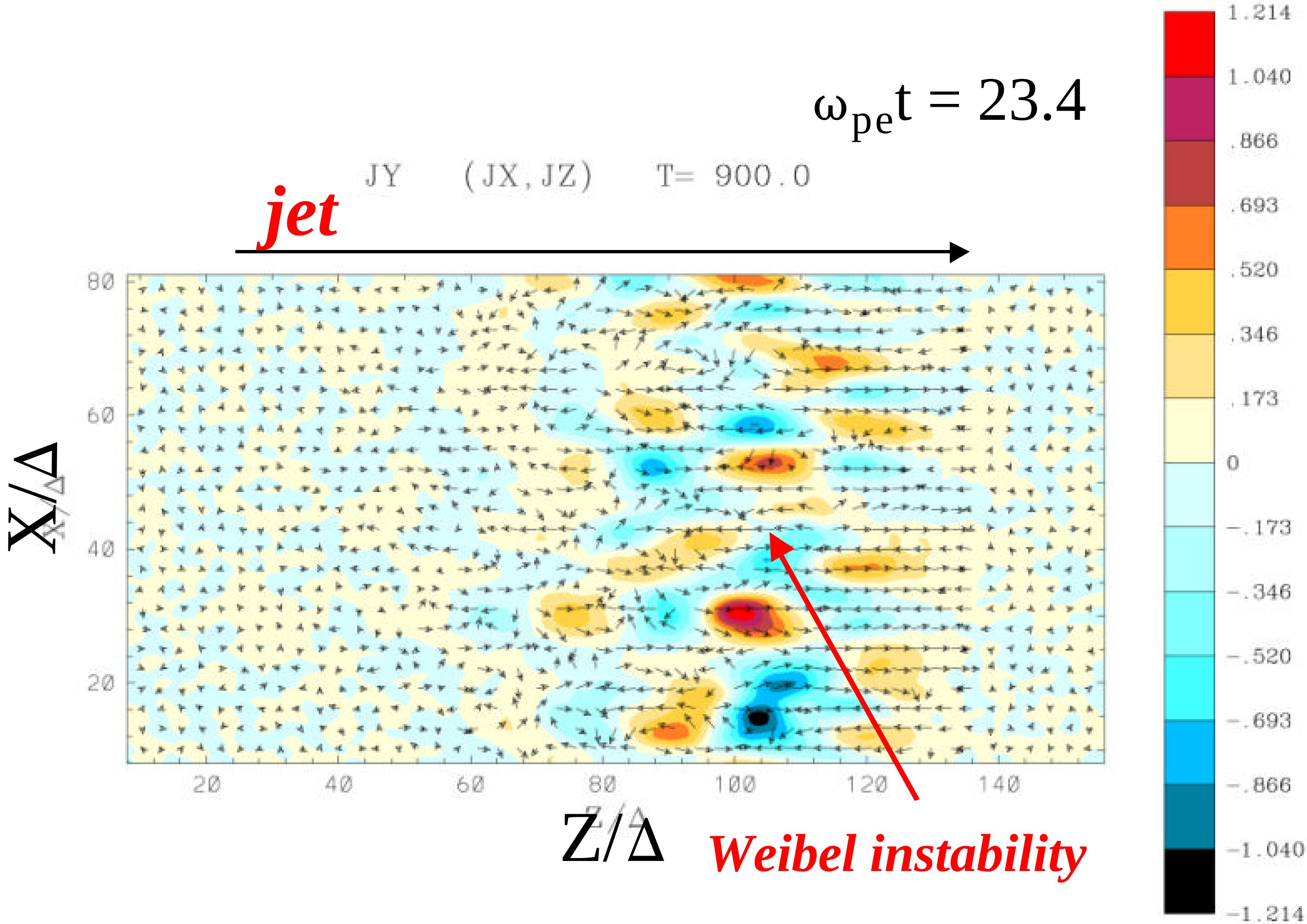
$\omega_{pe}t = 23.4$

current filamentation



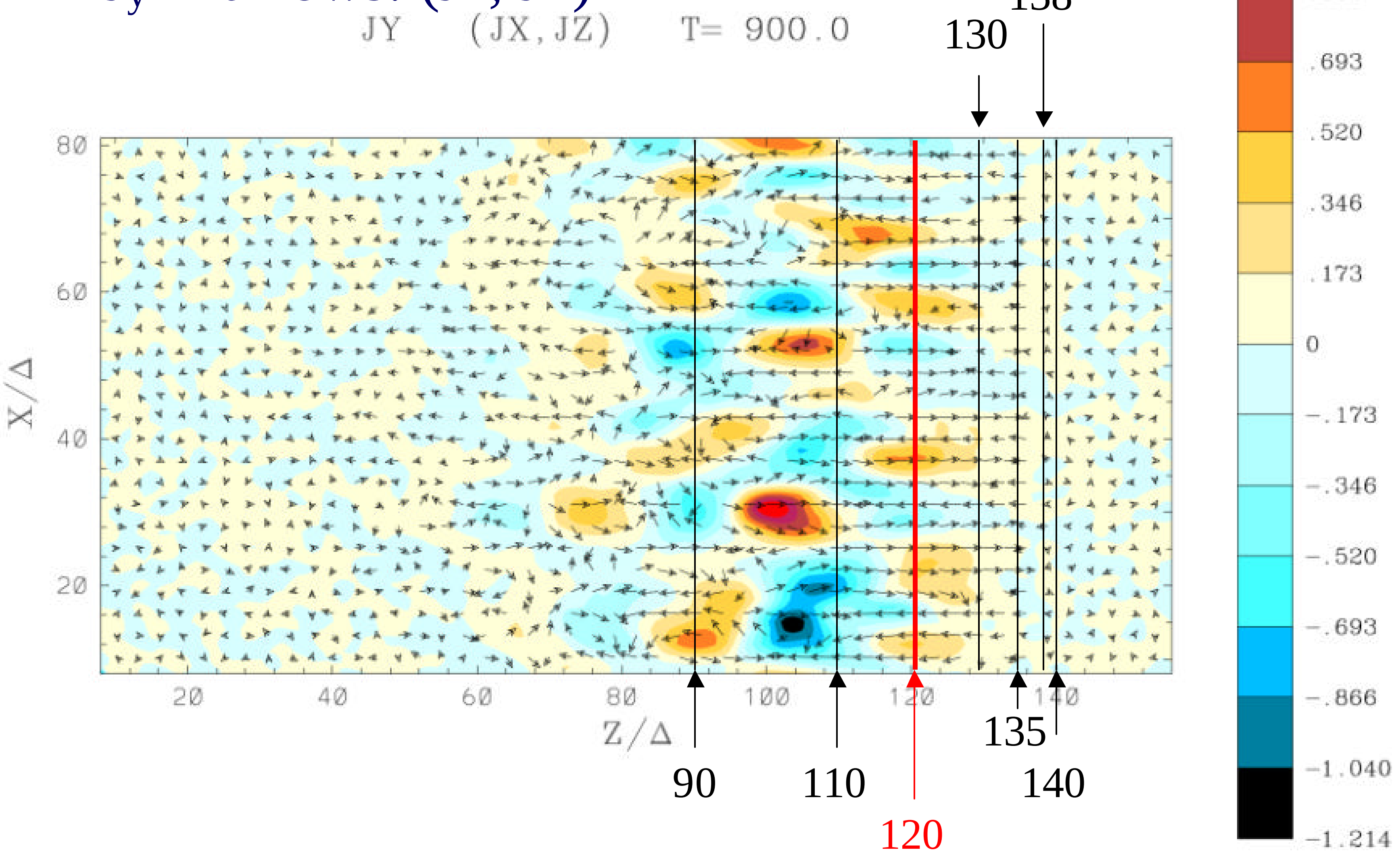


Perpendicular current J_y $(J_{z,x})$



Weibel instability $\qquad \omega_{pe}t = 23.4$

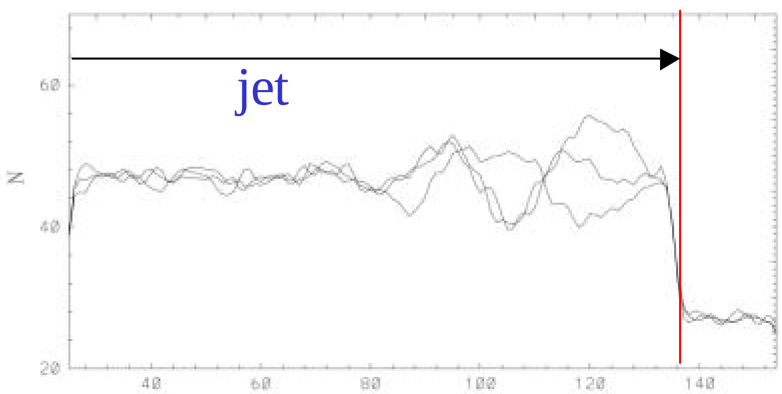
J_y arrows: (Jz, Jx)



1-d structure of jet dynamics

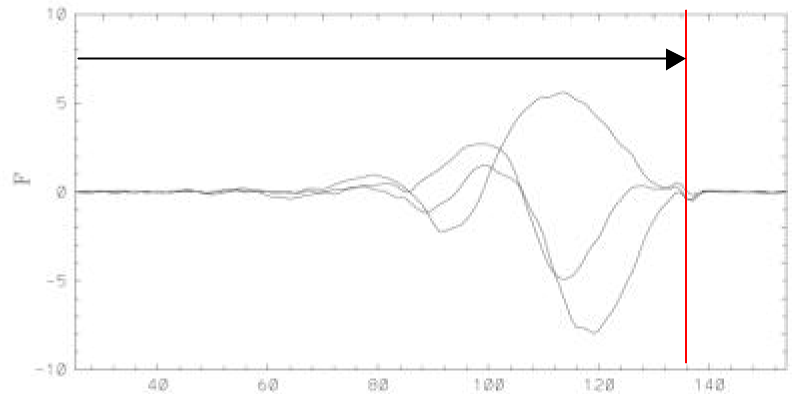
X/Δ = 38,
Y/Δ = 38, 43, 48

Electron density



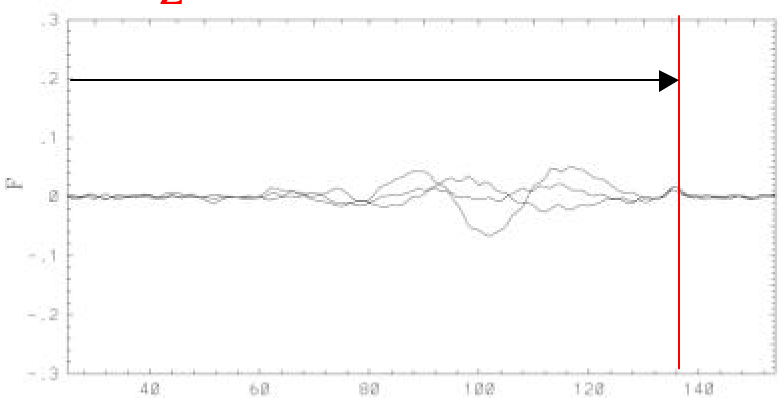
Z/Δ

J_Z



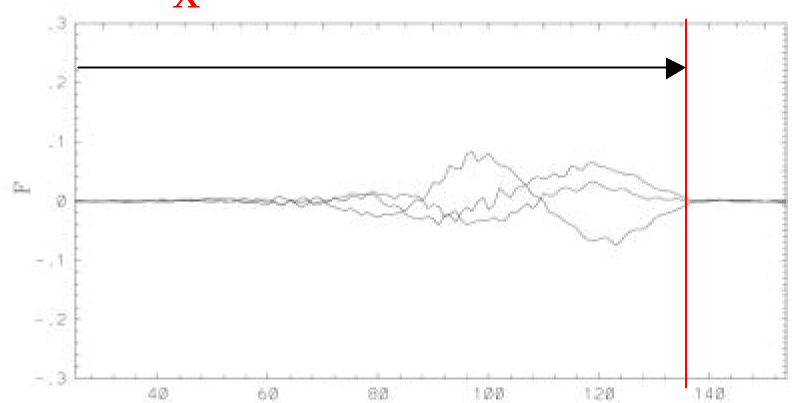
Z/Δ

E_z



Z/Δ

B_x

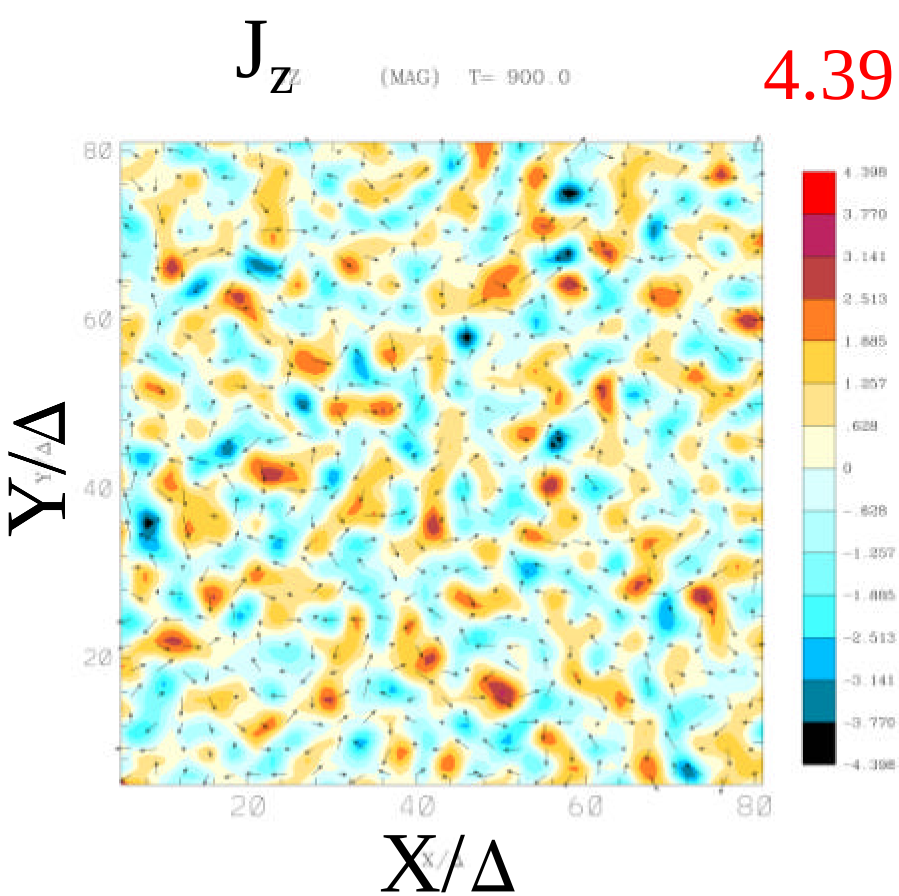


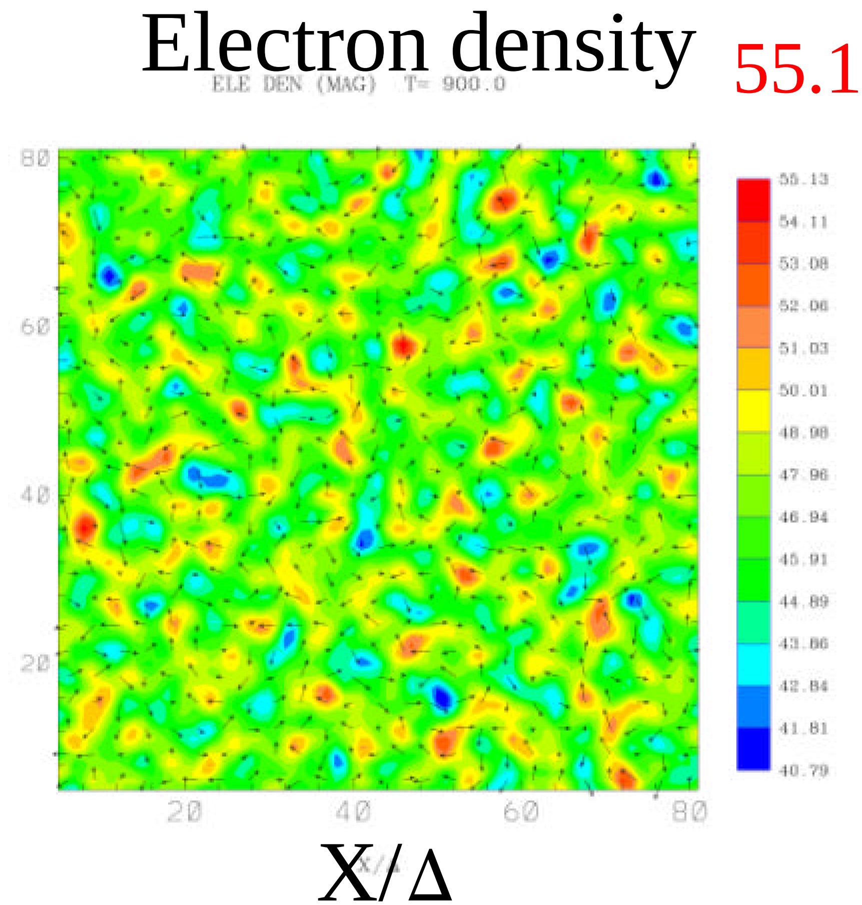
Z/Δ

Weibel instability seen in the x – y plane

$\omega_{pe}t = 23.4$ at $Z/\Delta = 120$ (just behind the shock front)

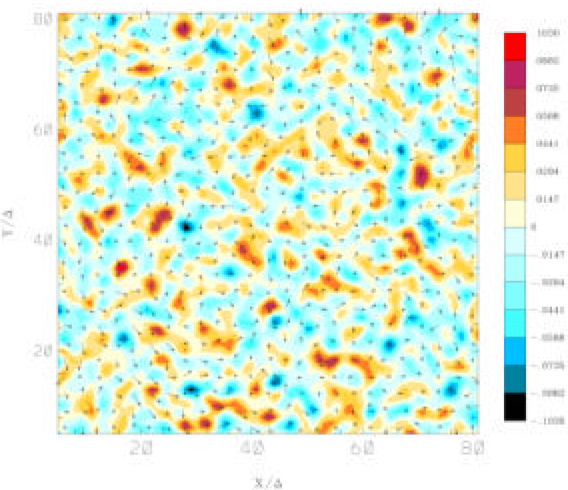
(arrows: magnetic fields)



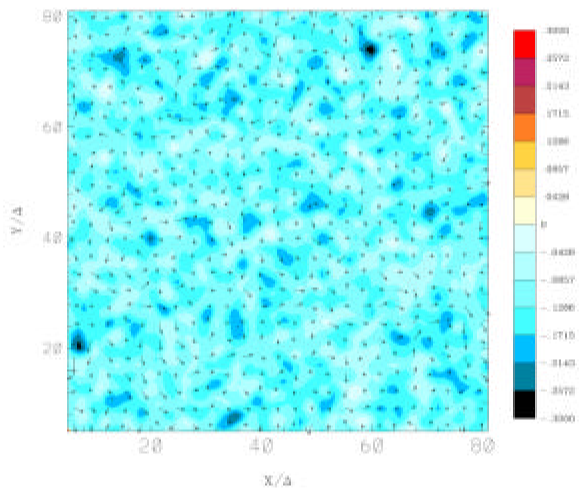


Dynamics of jet head in x-y plane Jz

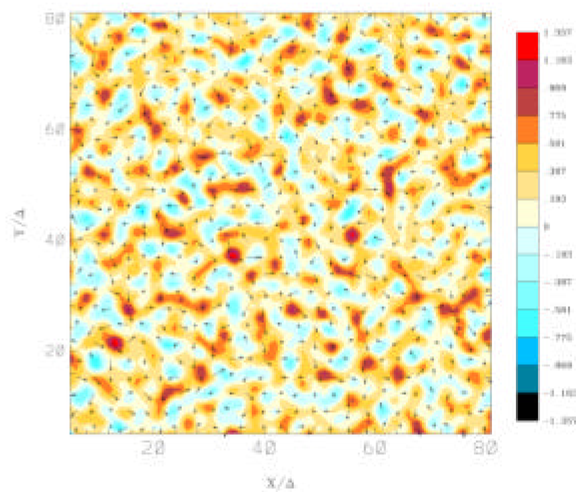
Z =140Δ **0.10**



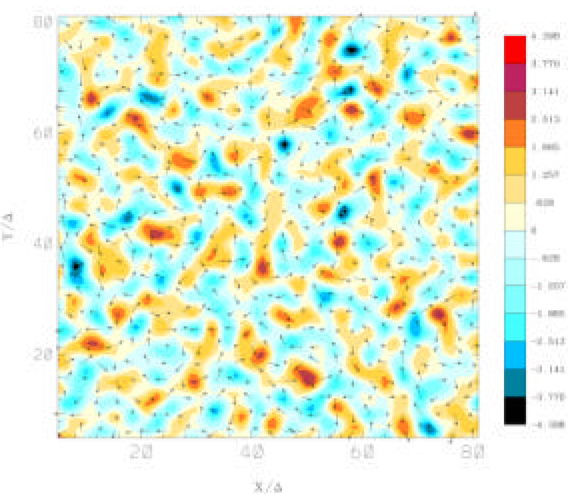
138Δ **0.30**



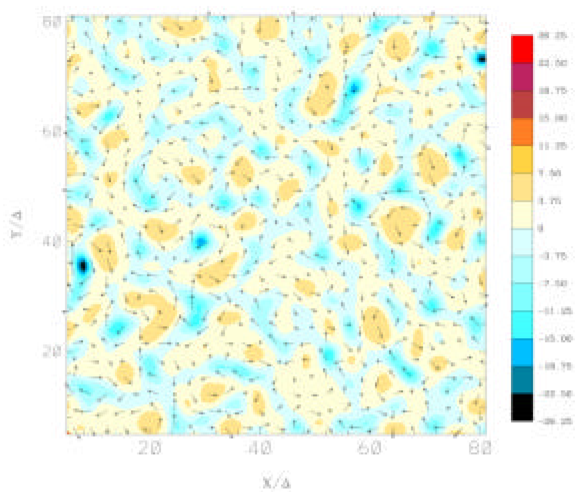
135Δ **1.35**



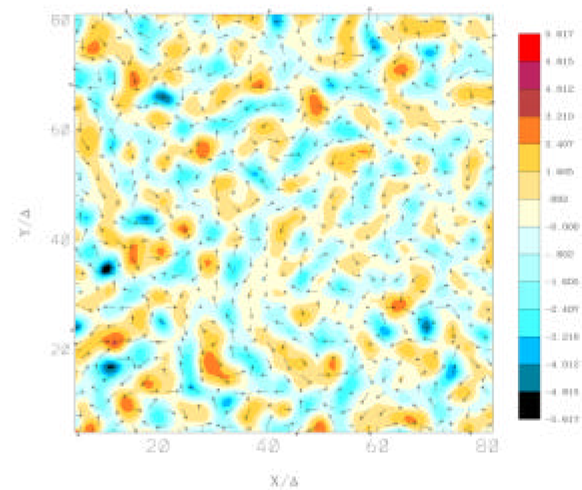
130Δ **4.39**



110Δ **~7.00**

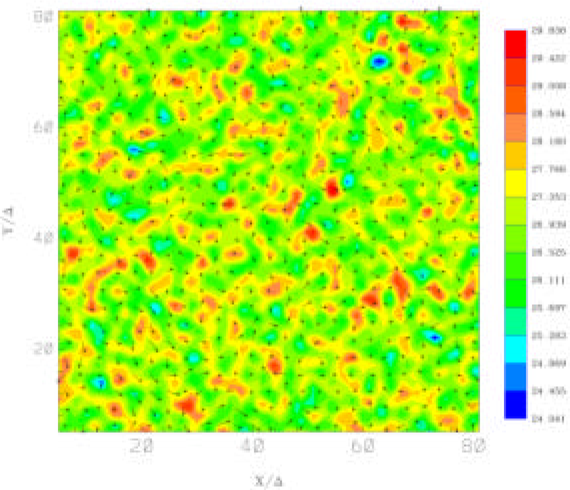


90Δ **5.61**

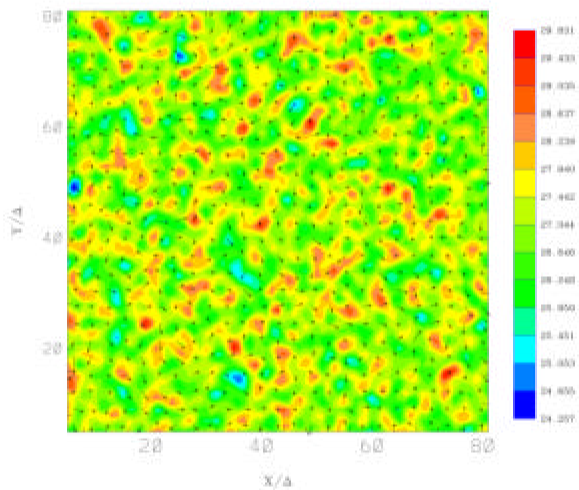


Dynamics of jet head Electron density $n_e \approx 50$

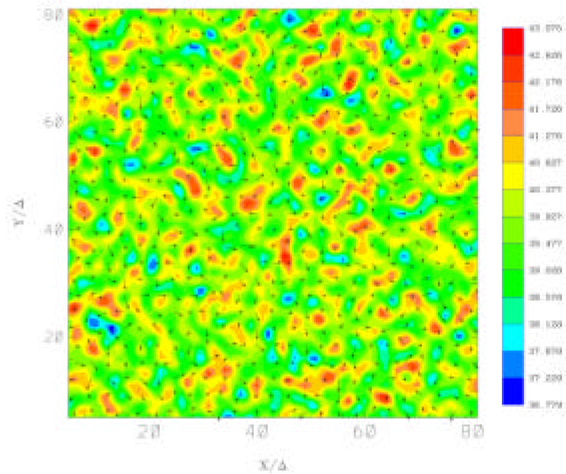
Z =140Δ **29.8**



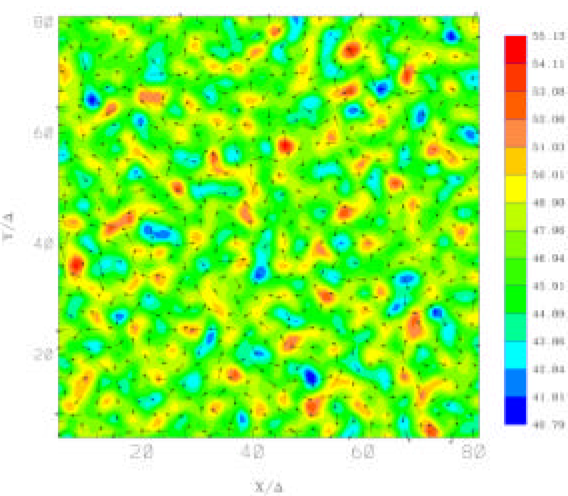
138Δ **29.8**



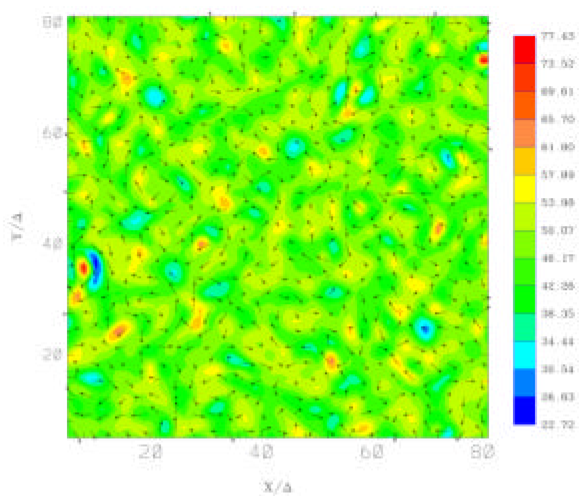
135Δ **43.0**



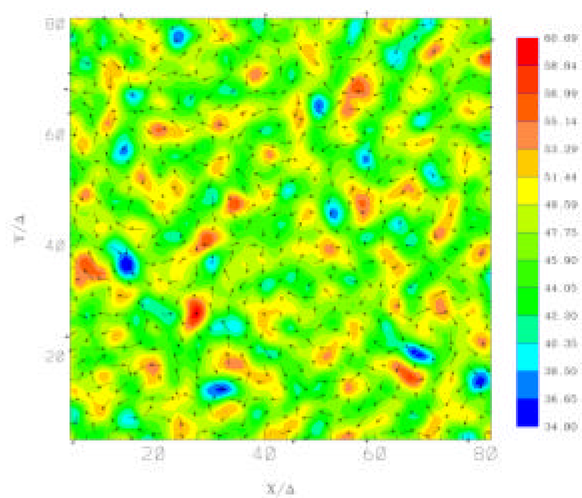
130Δ **55.1**



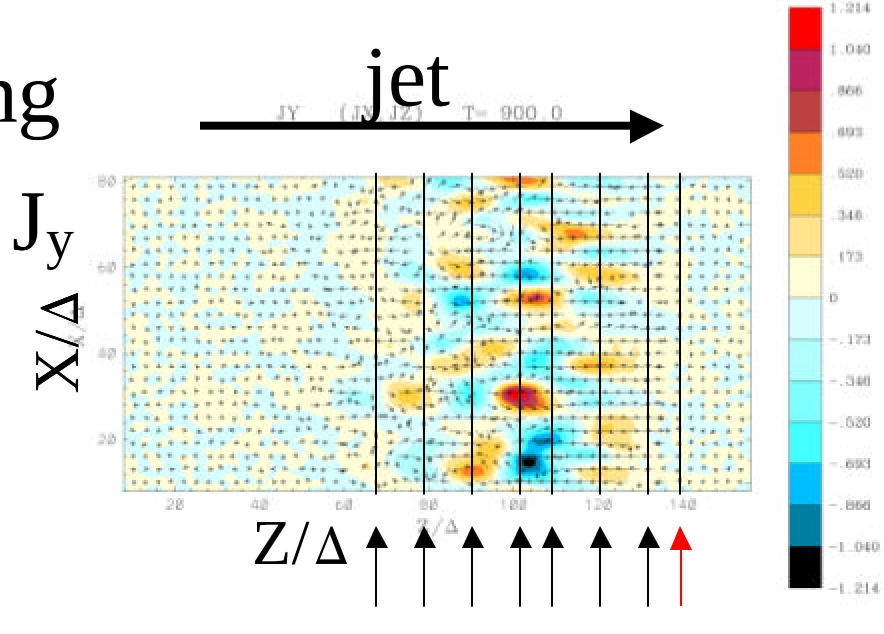
110Δ **77.4**



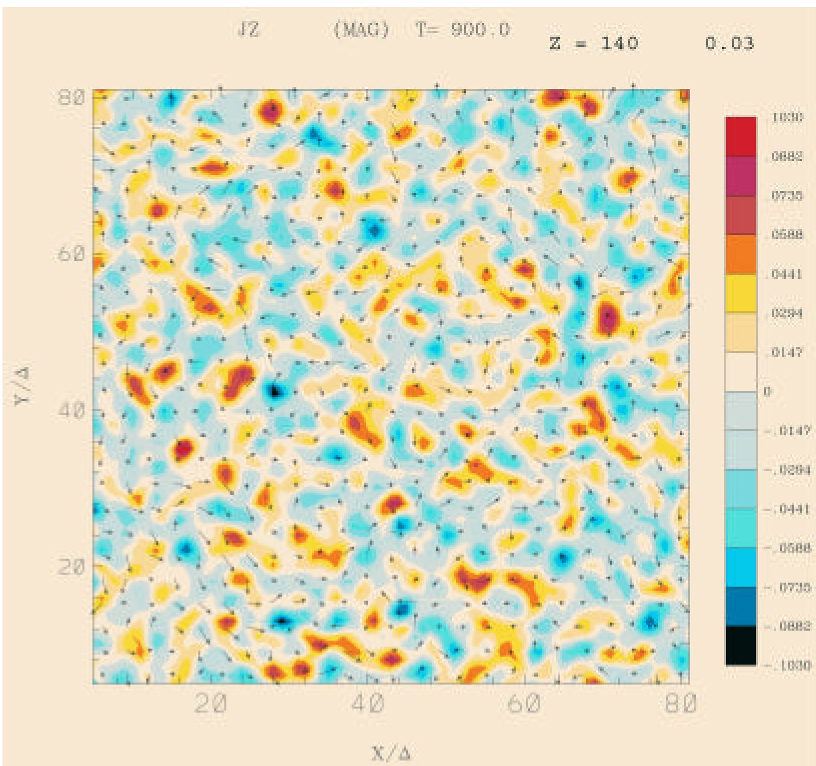
90Δ **60.6**



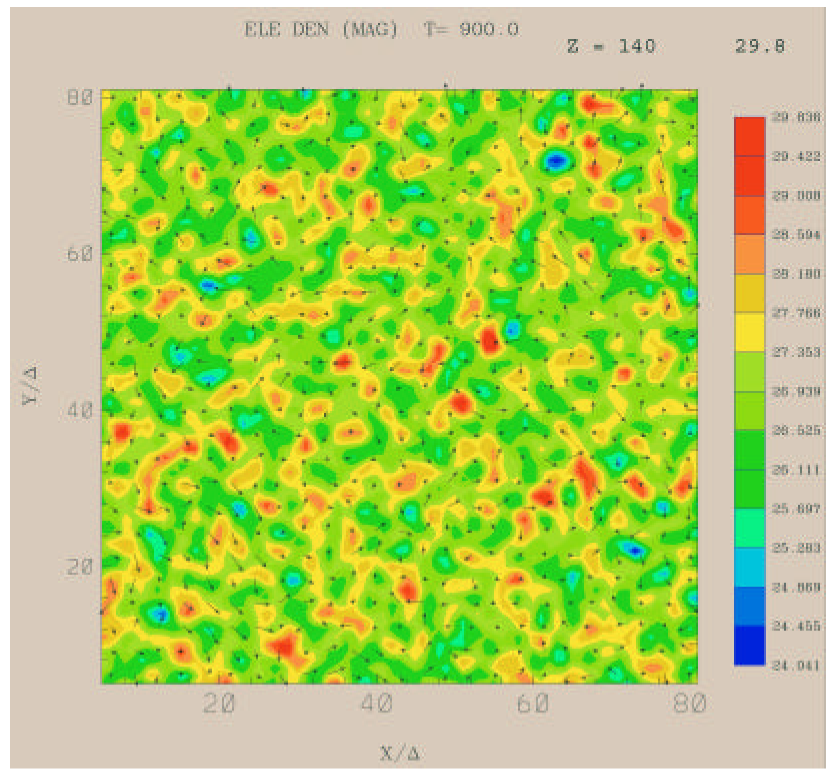
X-Y slicing



J_z λ_{ce}



Electron density



Flat electron-ion jet injected perpendicular to B

Electron-ion jet, $m_i/m_e = 20$

$\beta = v_j/c = 0.9798$, $v_{et}/c = 0.1$

$\gamma = (1-(v/c)^2)^{-1/2} = 5$

$v_{je} = 0.1 v_{et}$, $v_{ji} = 0.1 v_{it}$, $v_{it} = v_{et}$

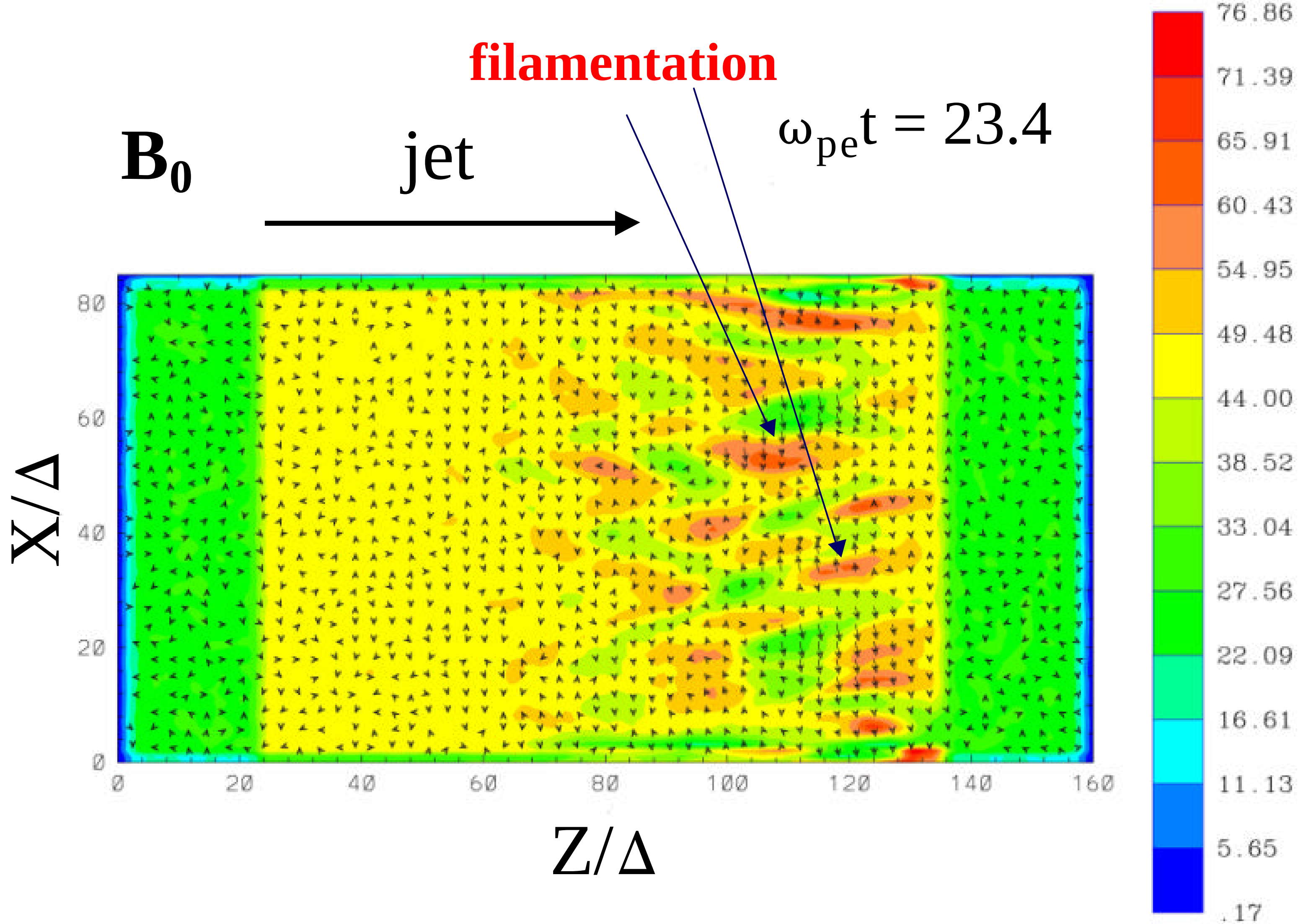
$\omega_{pe}/\Omega_e = 2.89$, $V_A/c = 0.0775$, $M_A = 12.66$

$\beta_e\ (= 8\pi n_e T_e/B^2) = 16.6$

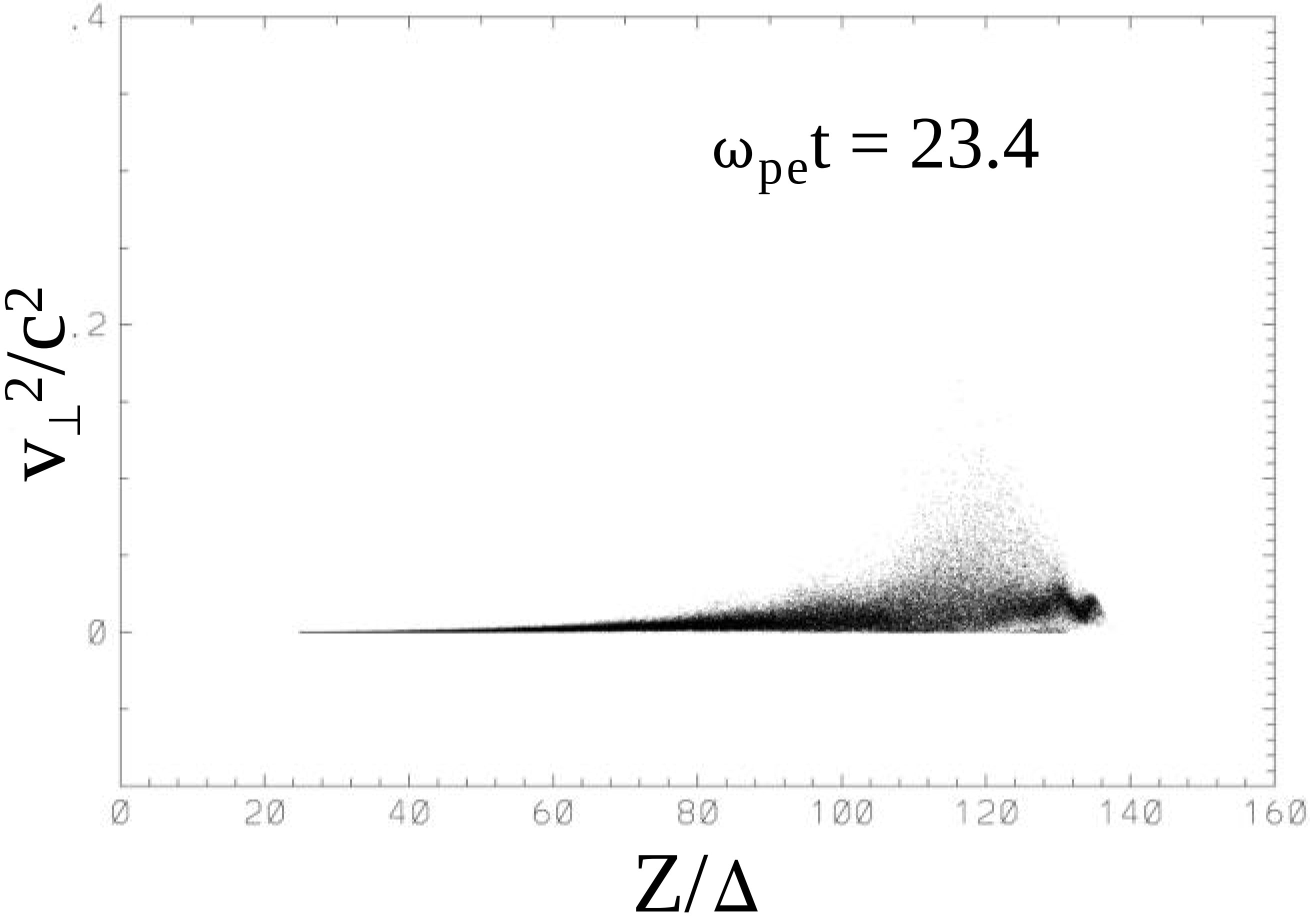
$\omega_{pe}\Delta t = 0.026$, $r_j = 40\ \Delta x \approx 10\ \lambda_{ce}$ (infinite width)

$n_j \approx 0.66 n_e$, $\rho_e = 13.89\Delta$, $\rho_i = 62.11\Delta$

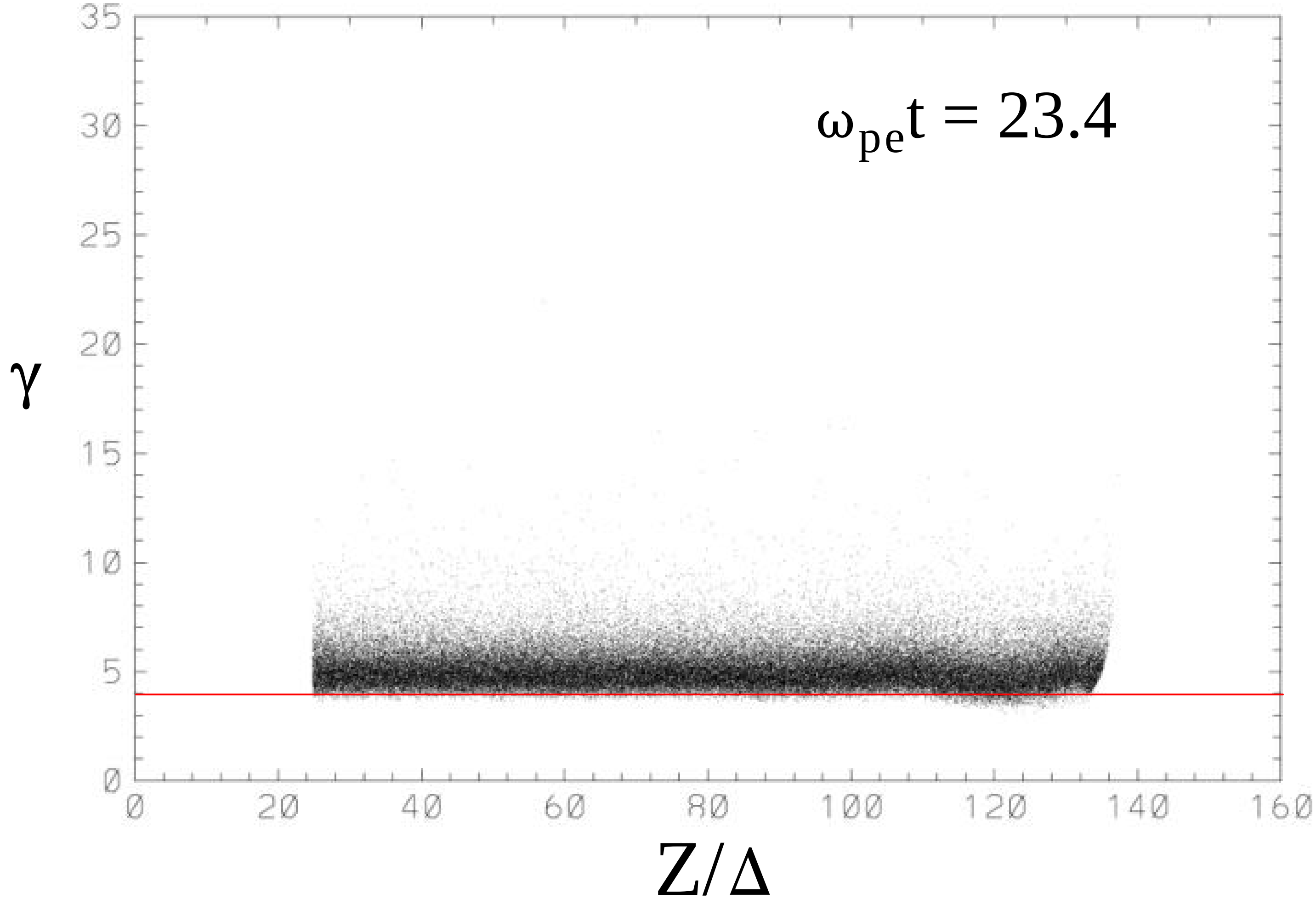
Electron density in z-x plane



Perpendicular particle acceleration (electrons)



Lorenz factor of electrons for flat electron-ion jet injected perpendicular to B



Summary

- **Simulation results show Weibel instability which creates filamented currents and density along the propagation of jets.**
- **The growth rate of Weibel instability depends on the size of jets, compositions, strength and direction of ambient magnetic fields.**
- **In a one-dimensional system Buneman instability is responsive to the surfing acceleration, Weibel instability is excited in the 3-D system.**
- **In order to understand the complex shock dynamics of relativistic jets, further simulations with additional physical mechanisms such as radiation loss and inverse Compton scattering are necessary.**

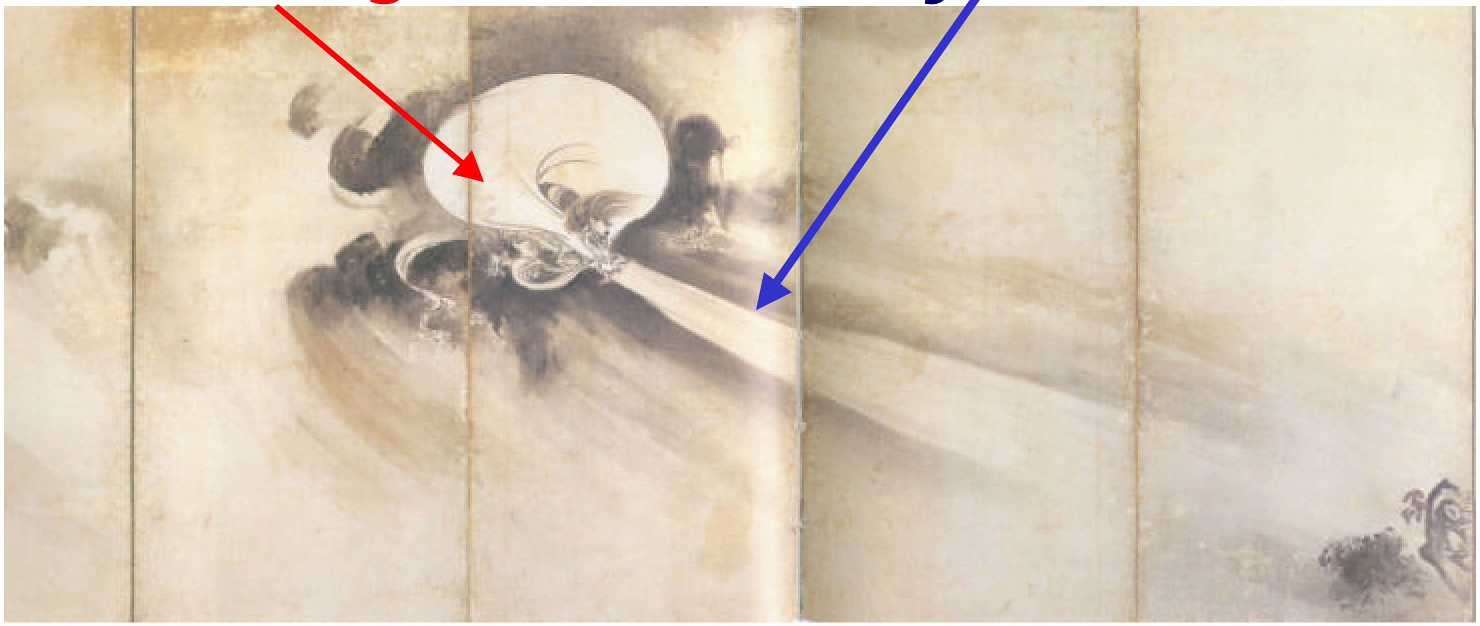
- The magnetic fields created by Weibel instability generate highly inhomogeneous magnetic fields, which is responsible for Jitter radiation (Medvedev, 2000, ApJ).
- Weibel instability may play a major role in particle acceleration in relativistic jets
- The dynamics of jet head is complicated and further investigation is necessary

Future plans for particle acceleration in relativistic jets

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics**
- **In order to investigate shock dynamics further diagnostics will be developed**
- **In order to improve the performance of the code, HPF or MPI will be used**
- **Implement better boundary conditions at the free boundaries**
- **Investigate synchrotron (jitter) emission from the accelerated electrons and compare with observations (Blazars and gamma-ray burst emissions)**
- **Develop a new code implementing synchrotron loss and/or inverse Compton scattering**
- **Compare simulation results with relativistic electro-positron experiments at SLAC to understand particle acceleration in astrophysical relativistic jets**

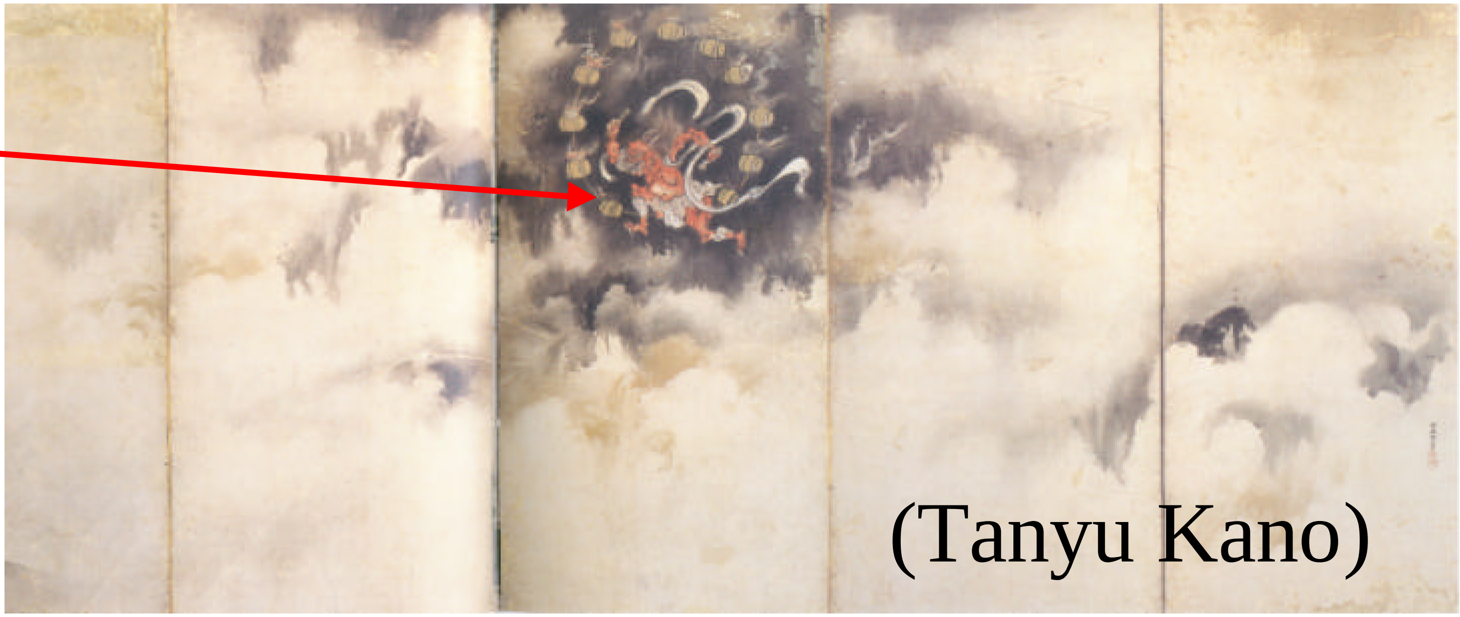
GRB engine

jet



Fushin

emission



Rashin

(Tanyu Kano)